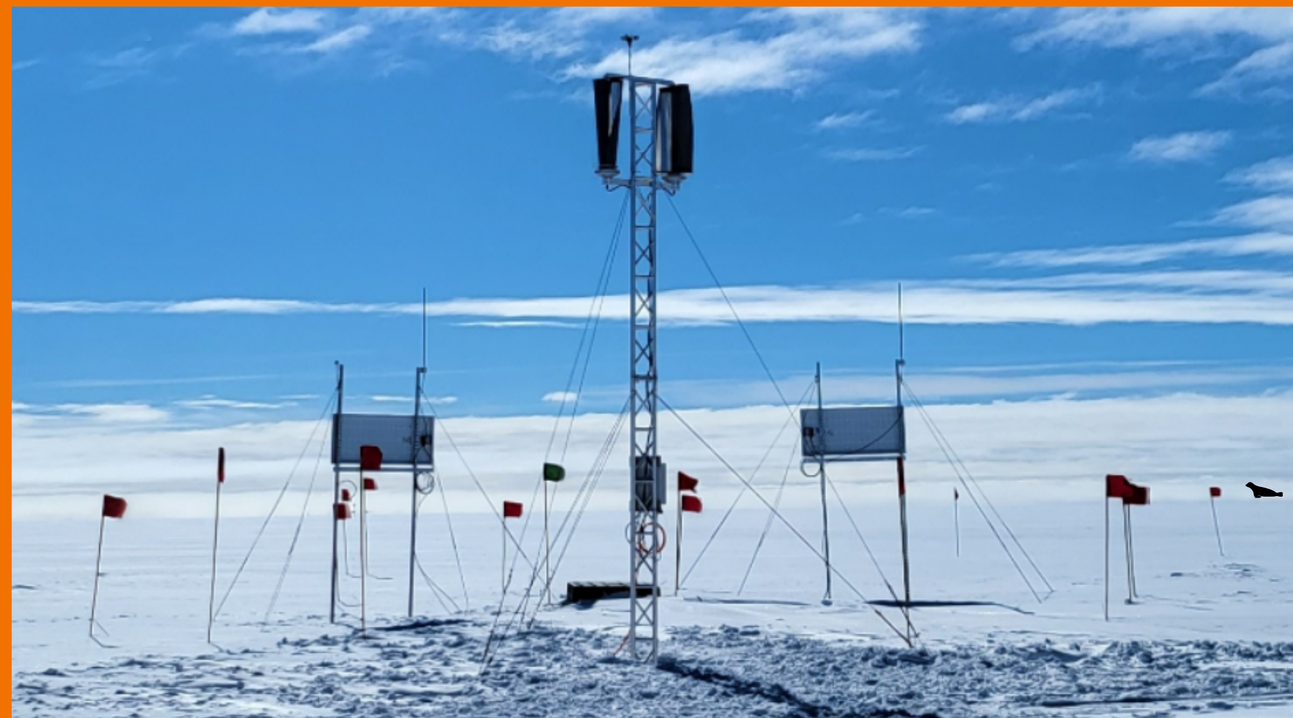
Hunting ultra-high-energy neutrinos with the Radio Neutrino Observatory in Greenland (RNO-G)

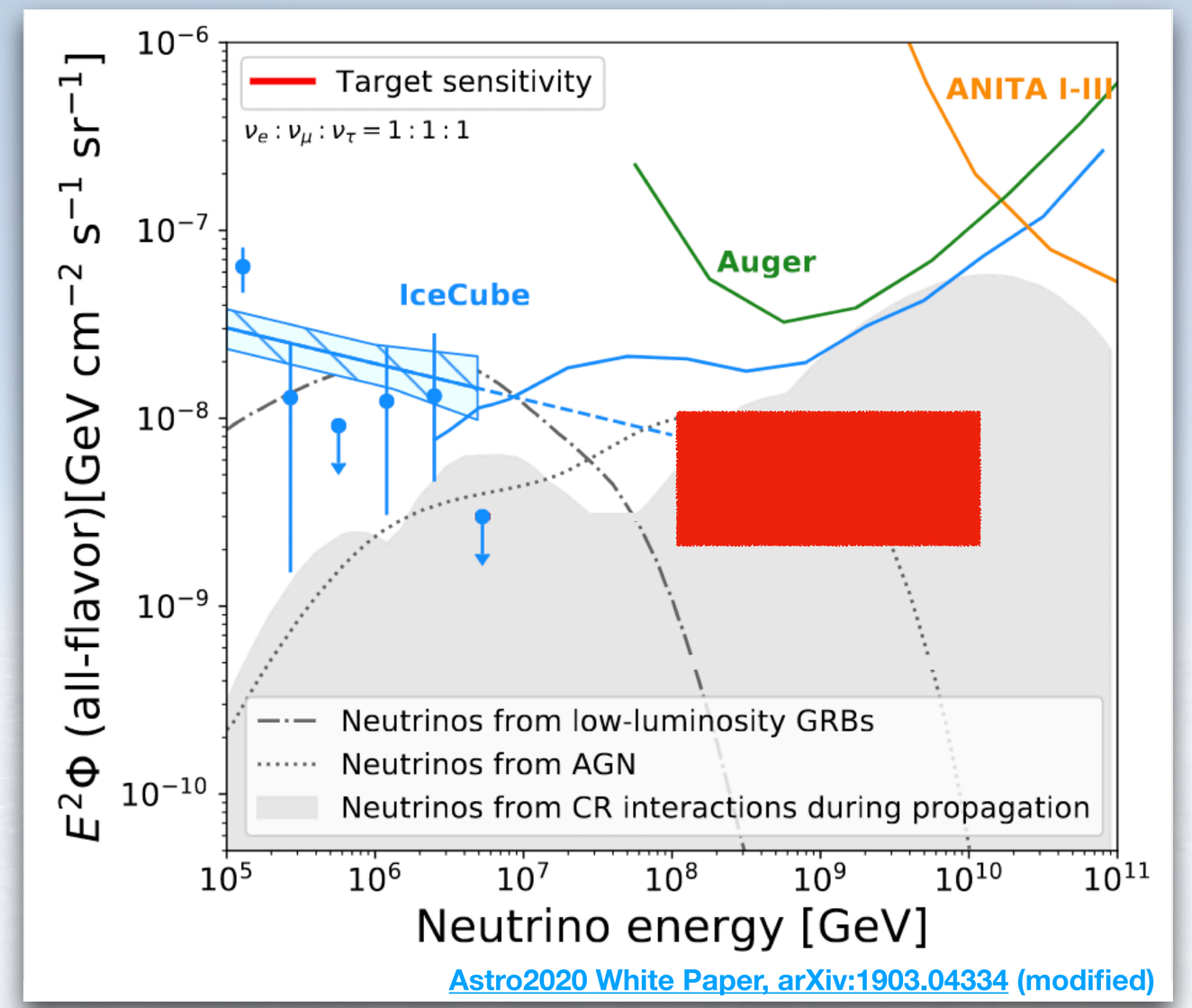
Felix Schlüter for the RNO-G group @ IIHE

Belgium Neutrino Meeting - 11.03.24



Ultra-high energies: Uncharted territory!

- Ultra-high-energy (UHE) neutrinos: 100 PeV - 10 EeV
  - We need 100 x IceCube
  - Cutoff in astrophysical spectrum
  - Test models of 2. astrophysical component
  - Test cosmogenic GZK neutrino flux



Astro2020 White Paper, arXiv:1903.04334 (modified)

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  - Overlapping FOV with IceCube
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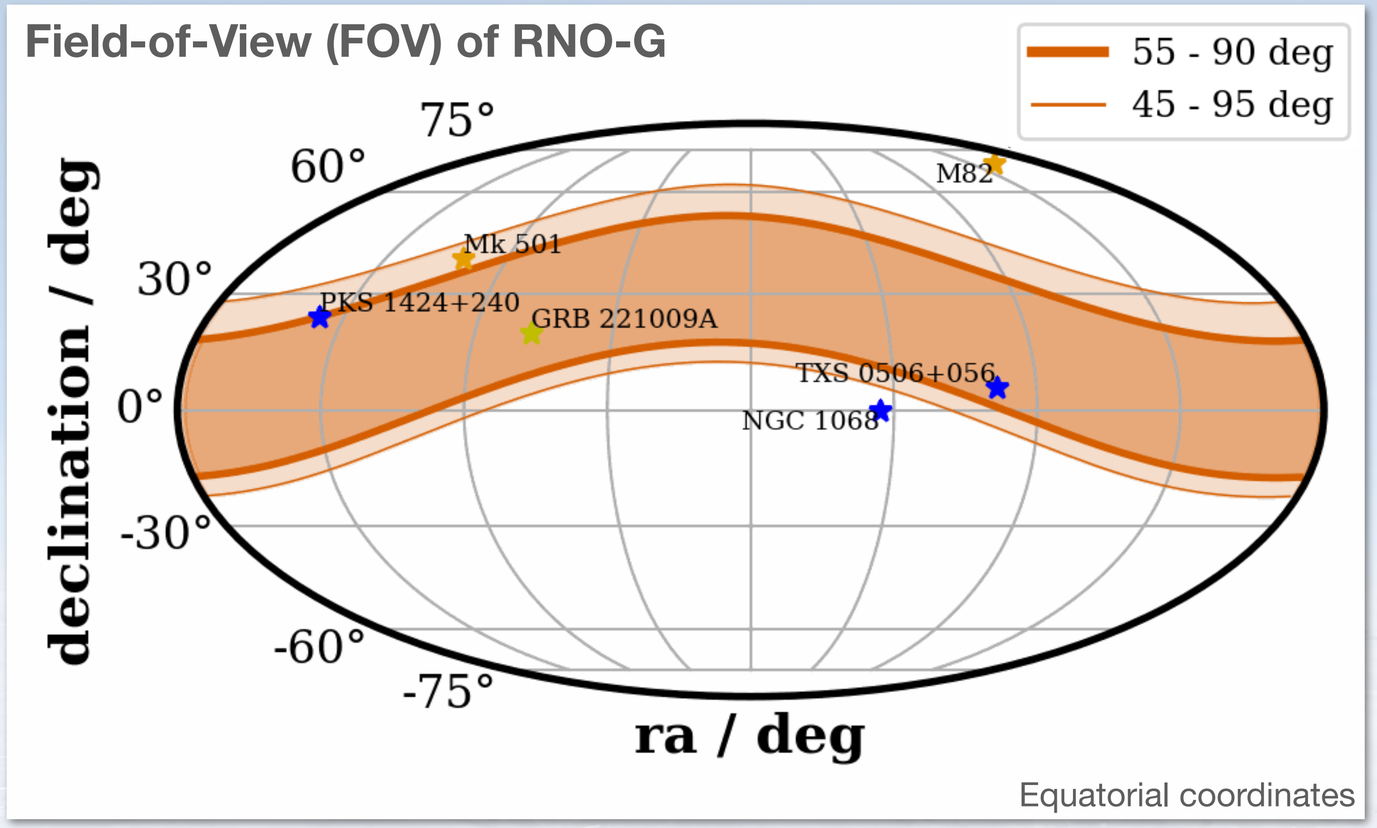

Neutrino sources (+ candidate)

Strong gamma ray sources

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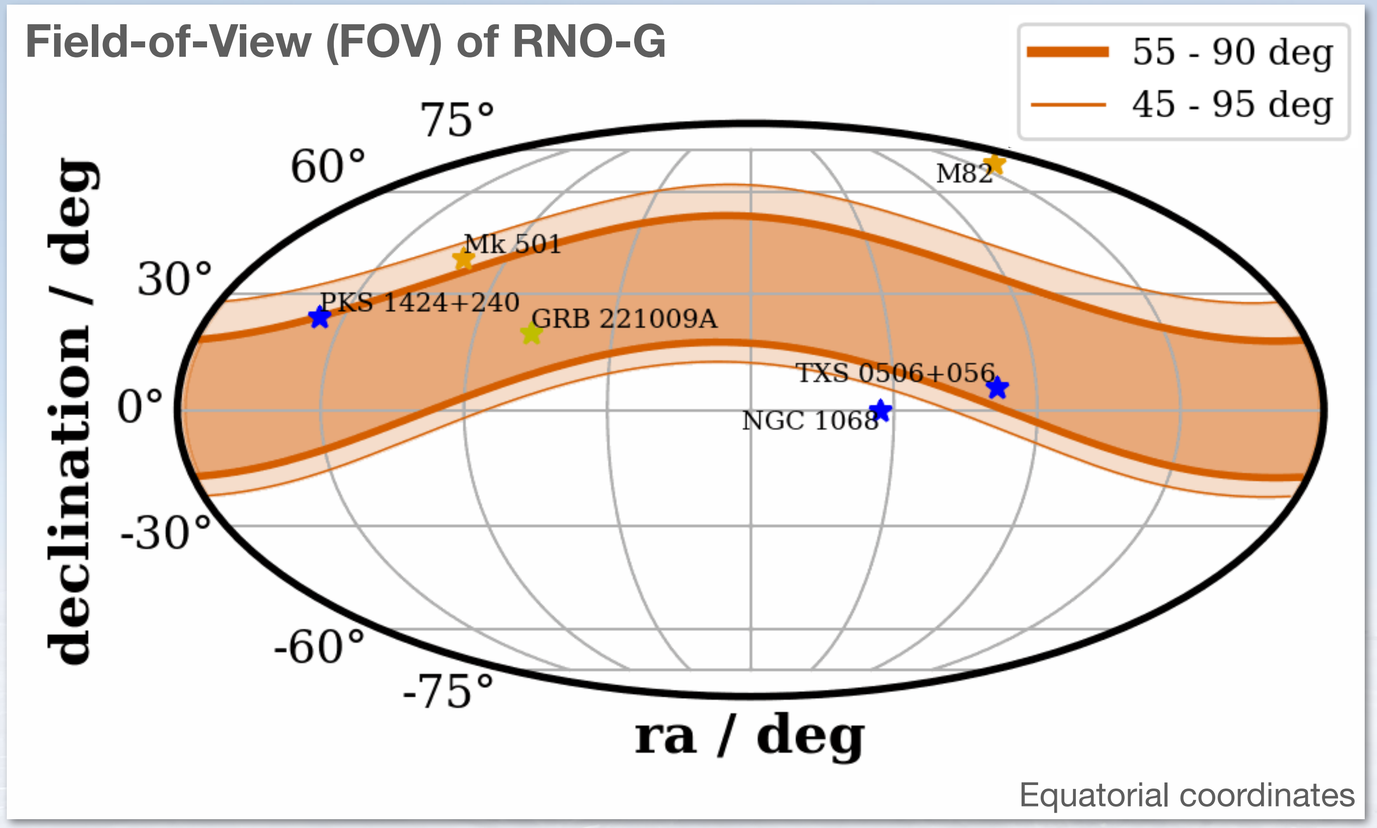

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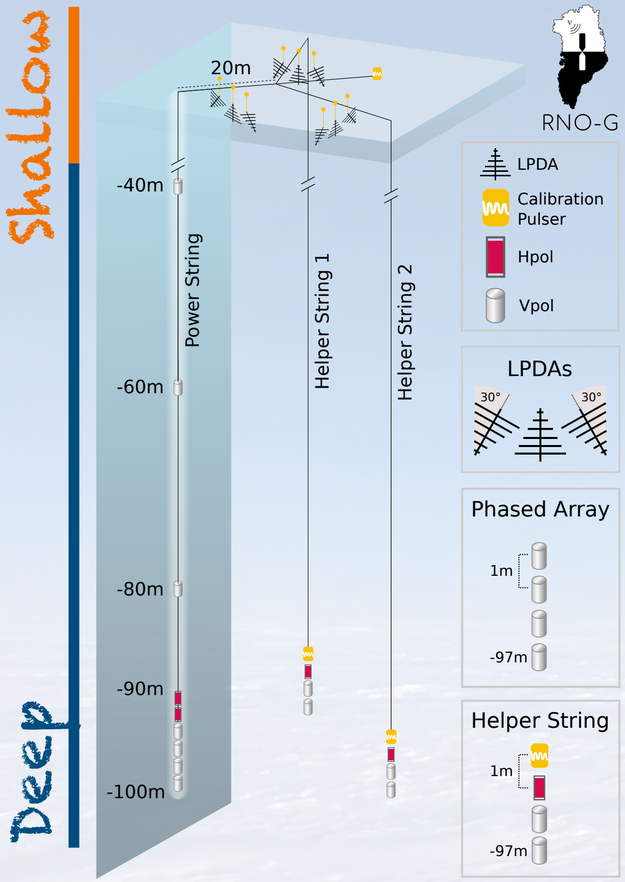
Radio Neutrino Observatory - Greenland

More pictures later 😇

Hybrid station with 24 antennas



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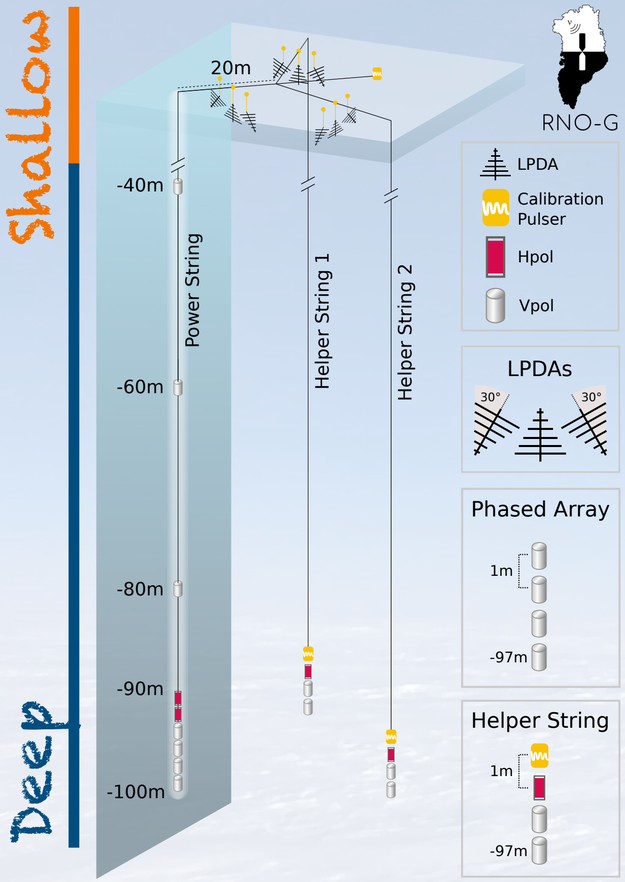

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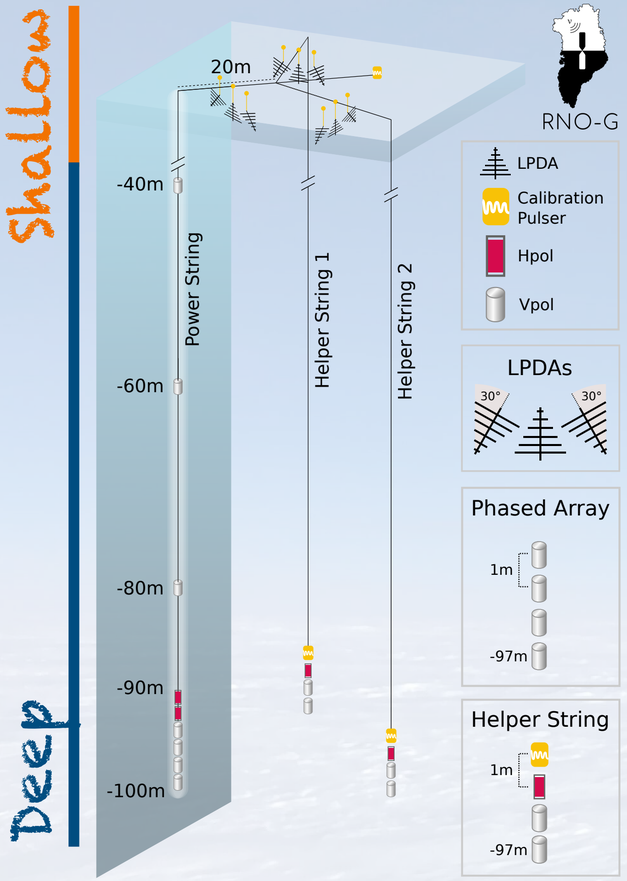
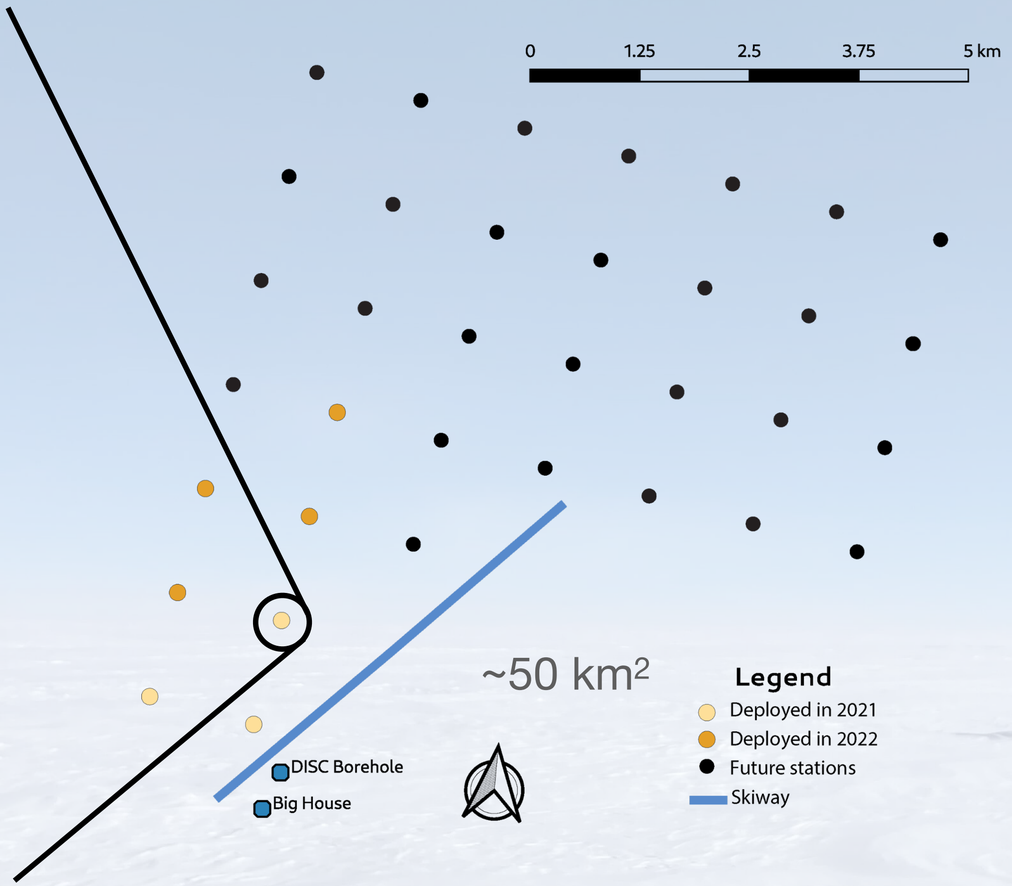


35 stations on 1.25 km grid



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- Fully funded (3 more seasons)
- Each station acts as independent detector

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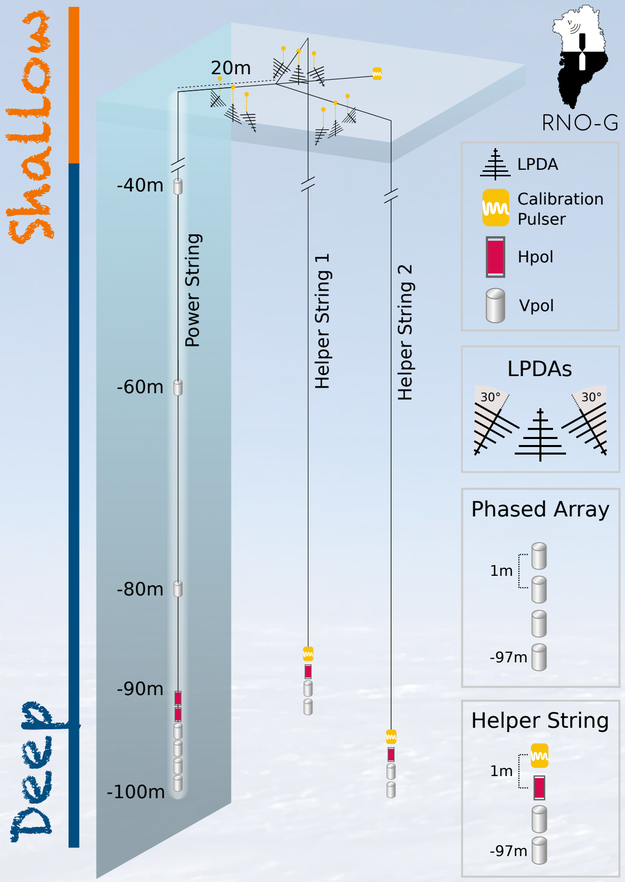

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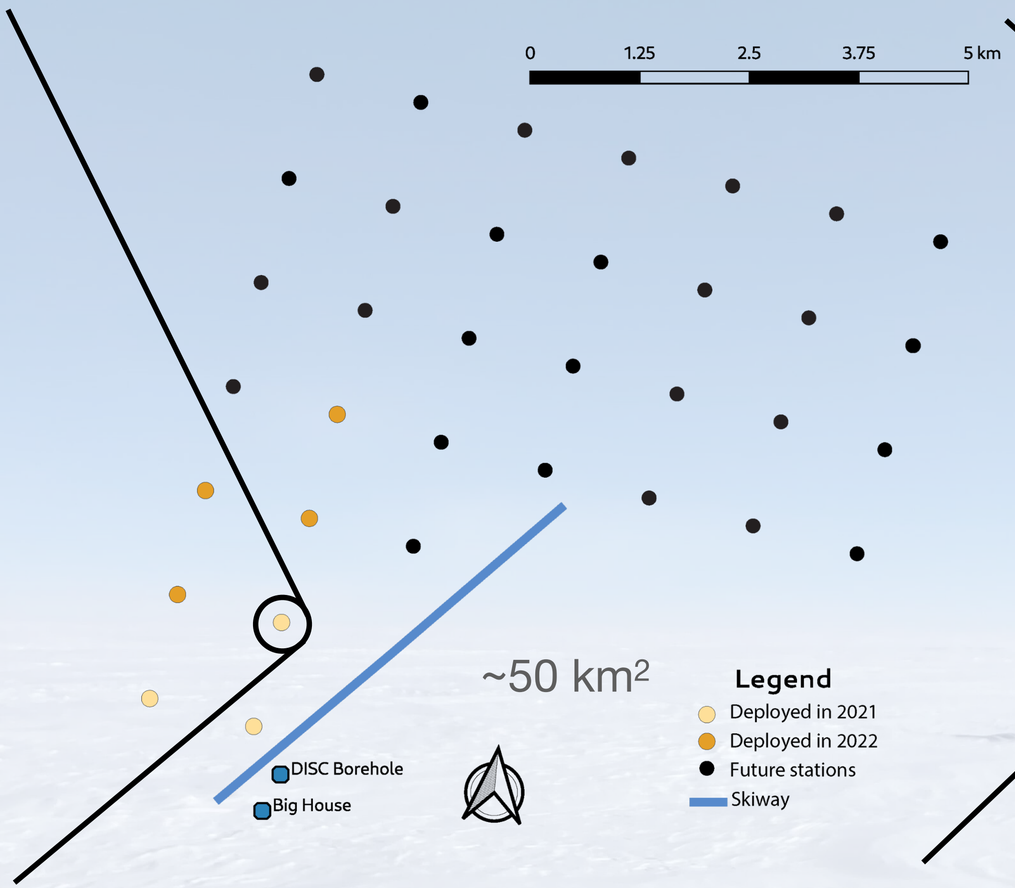
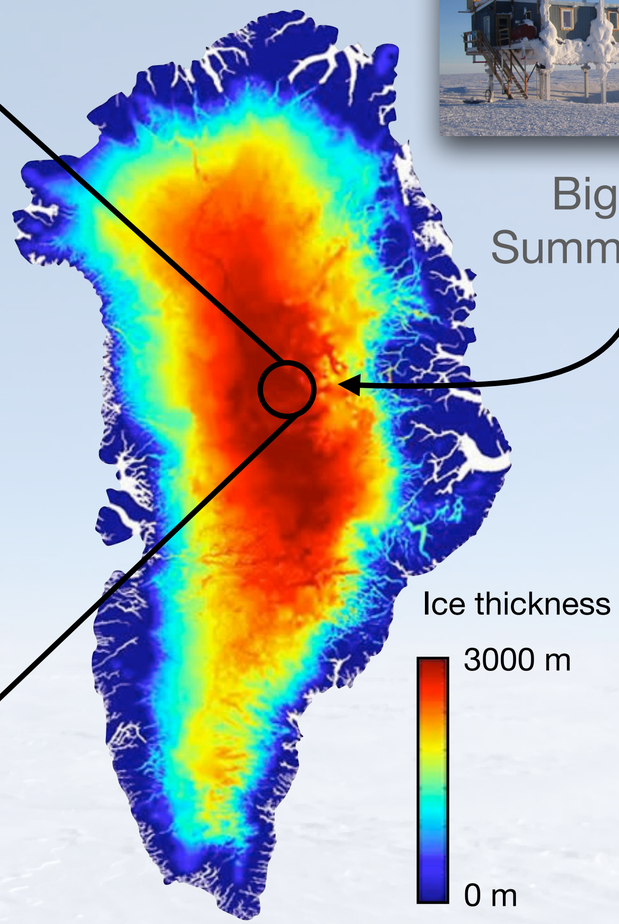


Greenland

Big house @ Summit Station



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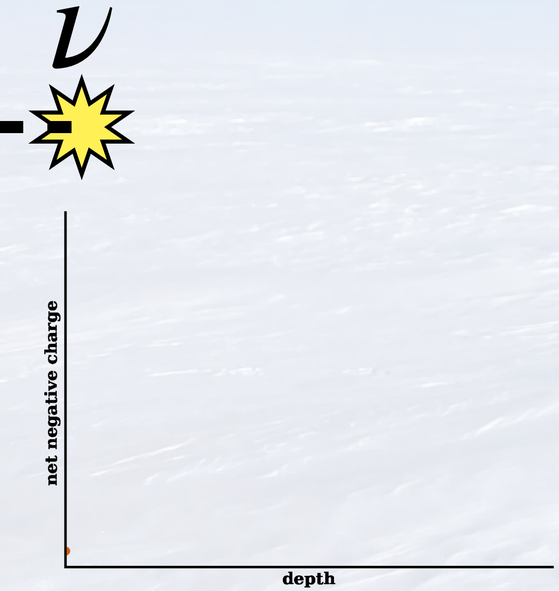
- +3km of natural clean ice
- Existing infrastructure
- 10 months of sunlight per year

Radio detection of neutrinos



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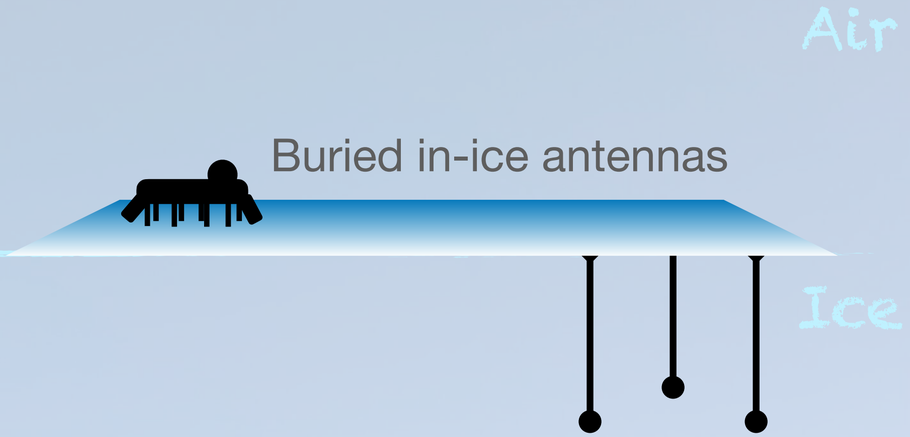
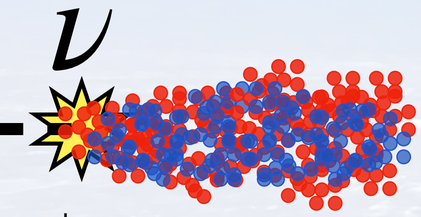


Particle cascade

E_{min} to detect radio emission $\gtrsim$ 10 PeV



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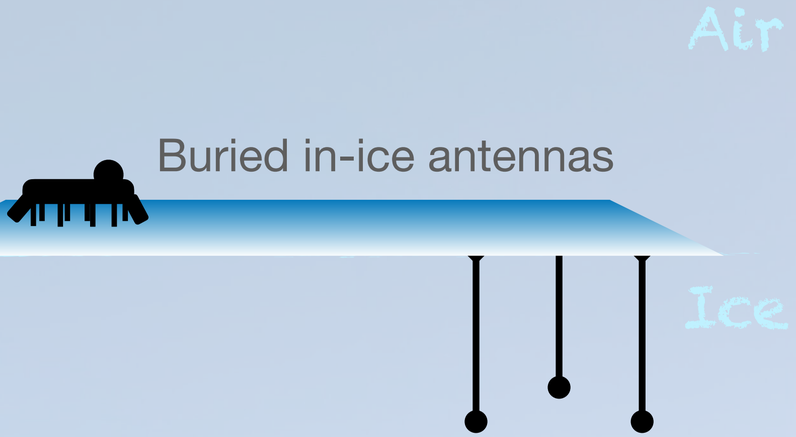

Radio emission pattern has cone shape due to interference

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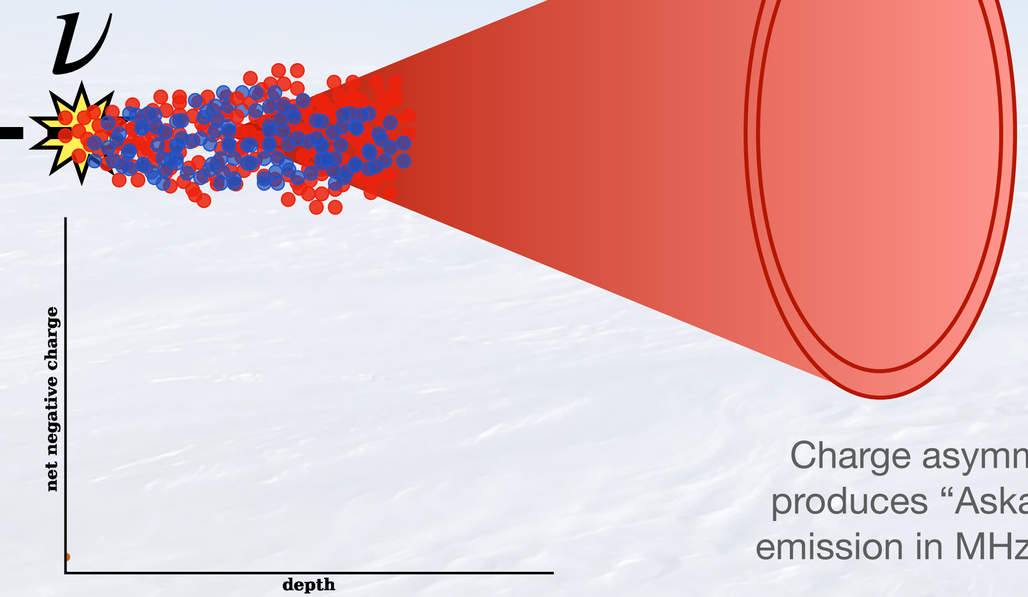

Charge asymmetry produces “Askaryan” emission in MHz - GHz

Radio detection of neutrinos

Air

Buried in-ice antennas

Ice

Radio emission pattern has cone shape due to interference

Bend trajectory due to refractive index of ice

Attenuation length $\mathcal{O}(1\text{km})$

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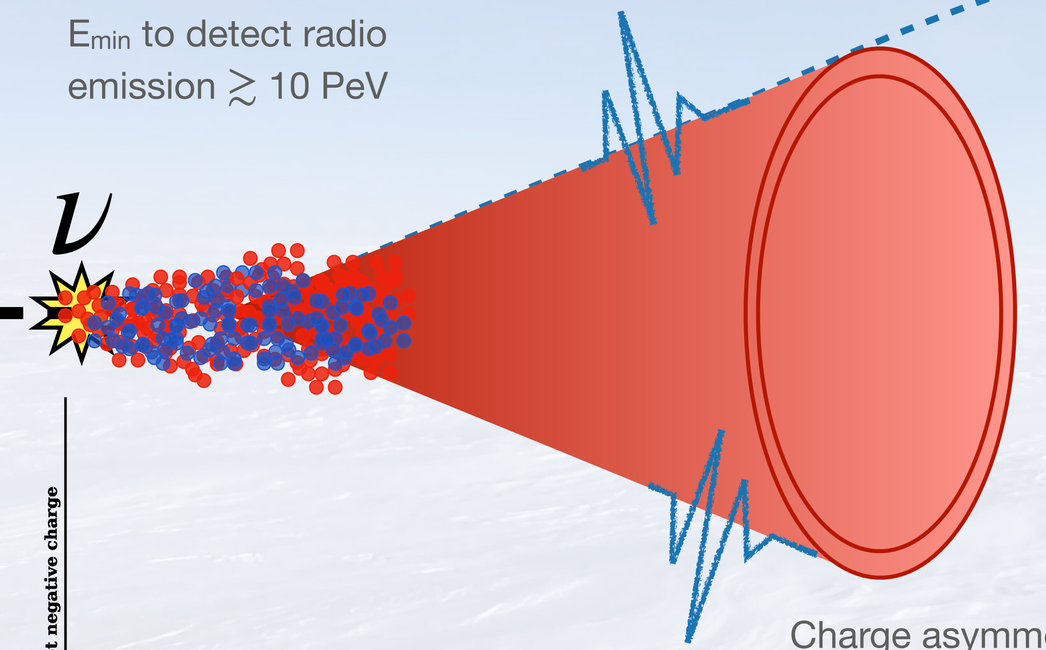

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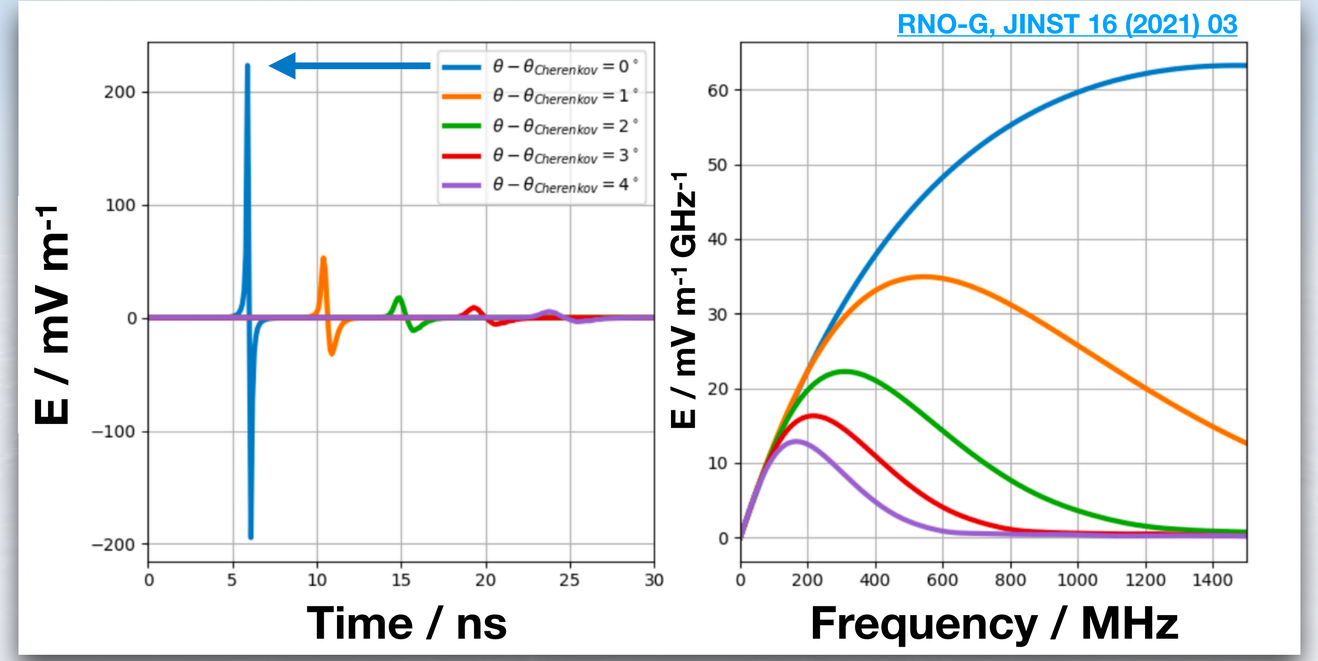
RNO-G, JINST 16 (2021) 03



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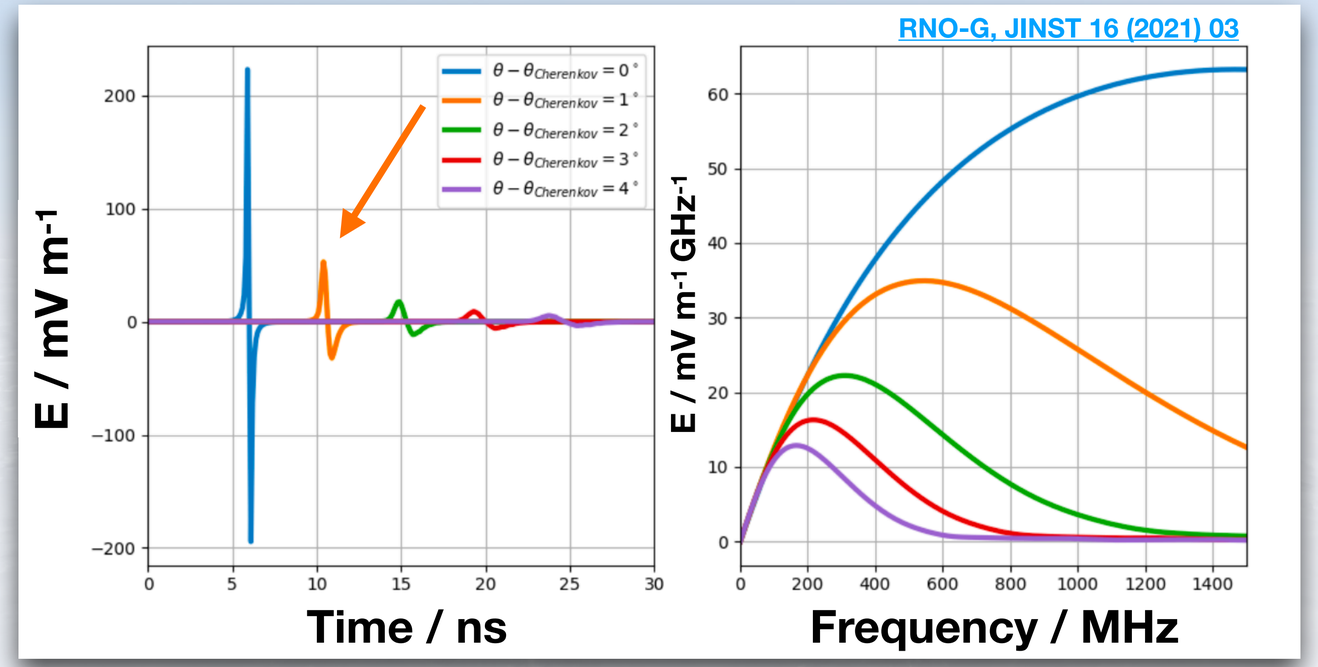
$\theta_{\text{view}} - \theta_{\text{Che}}$

Change viewing angle θ_{view} reduces signal (higher frequencies vanish)



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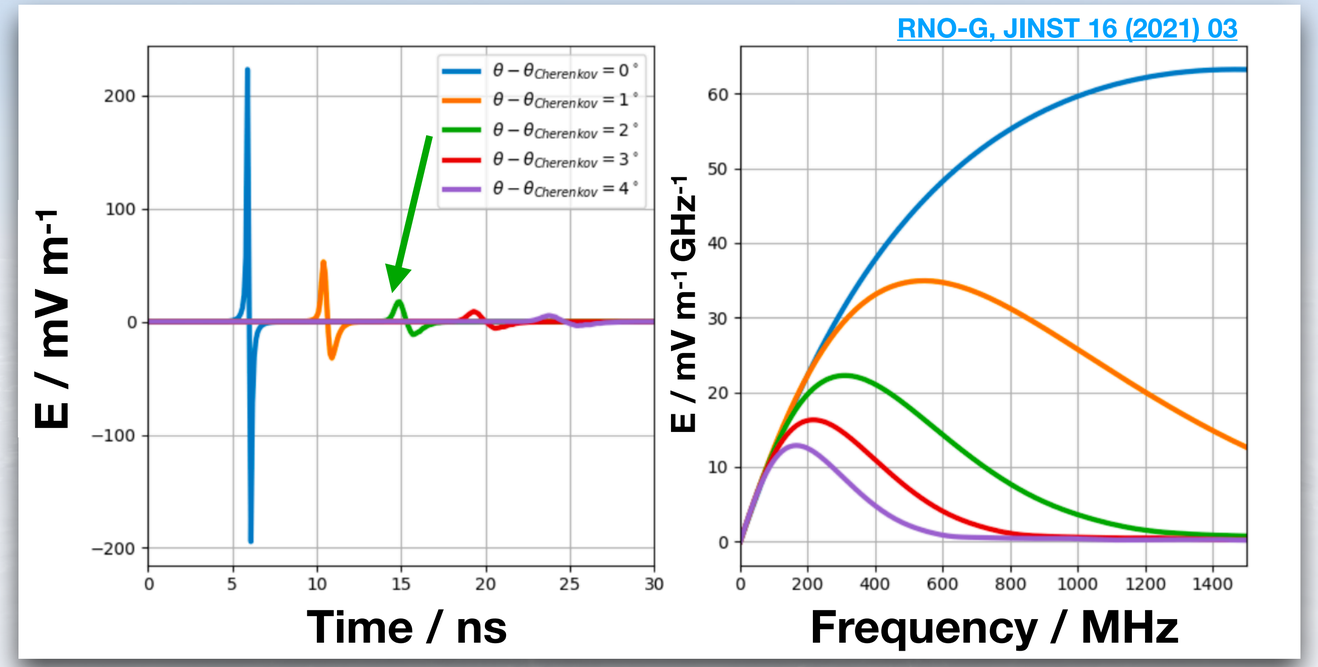

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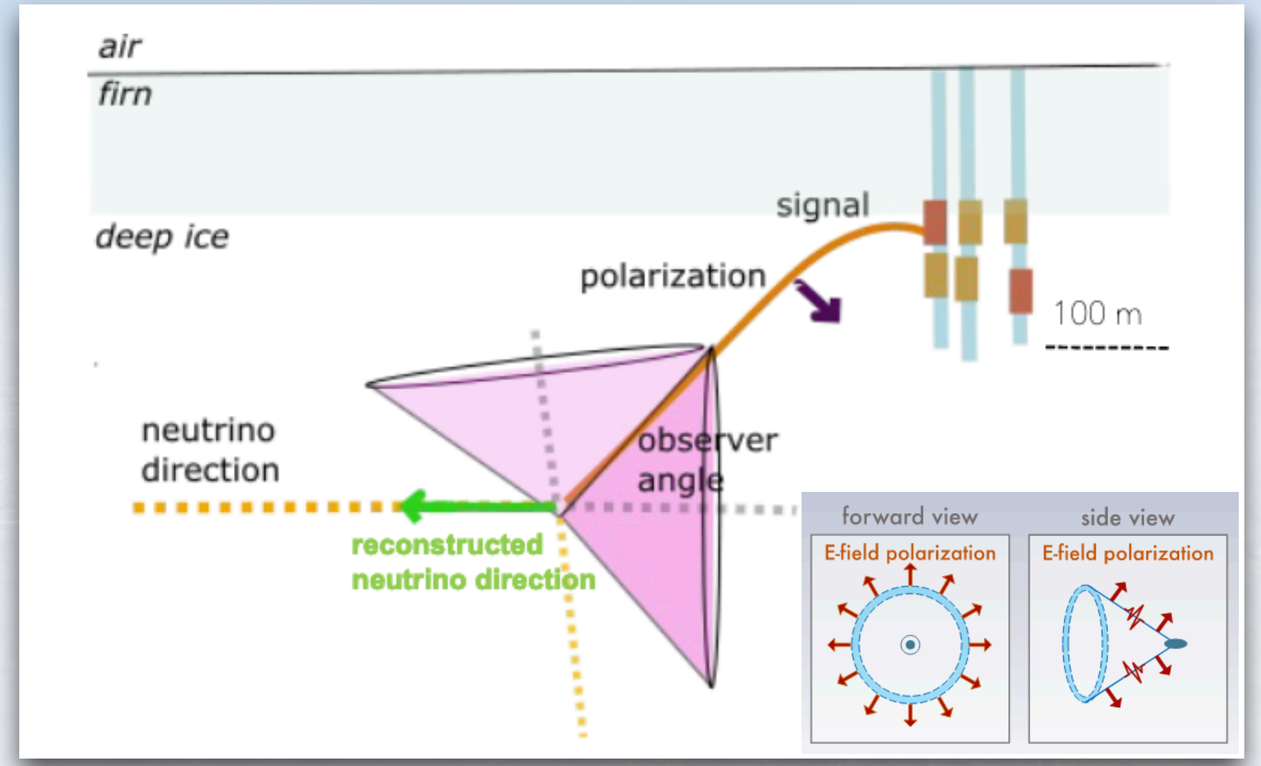
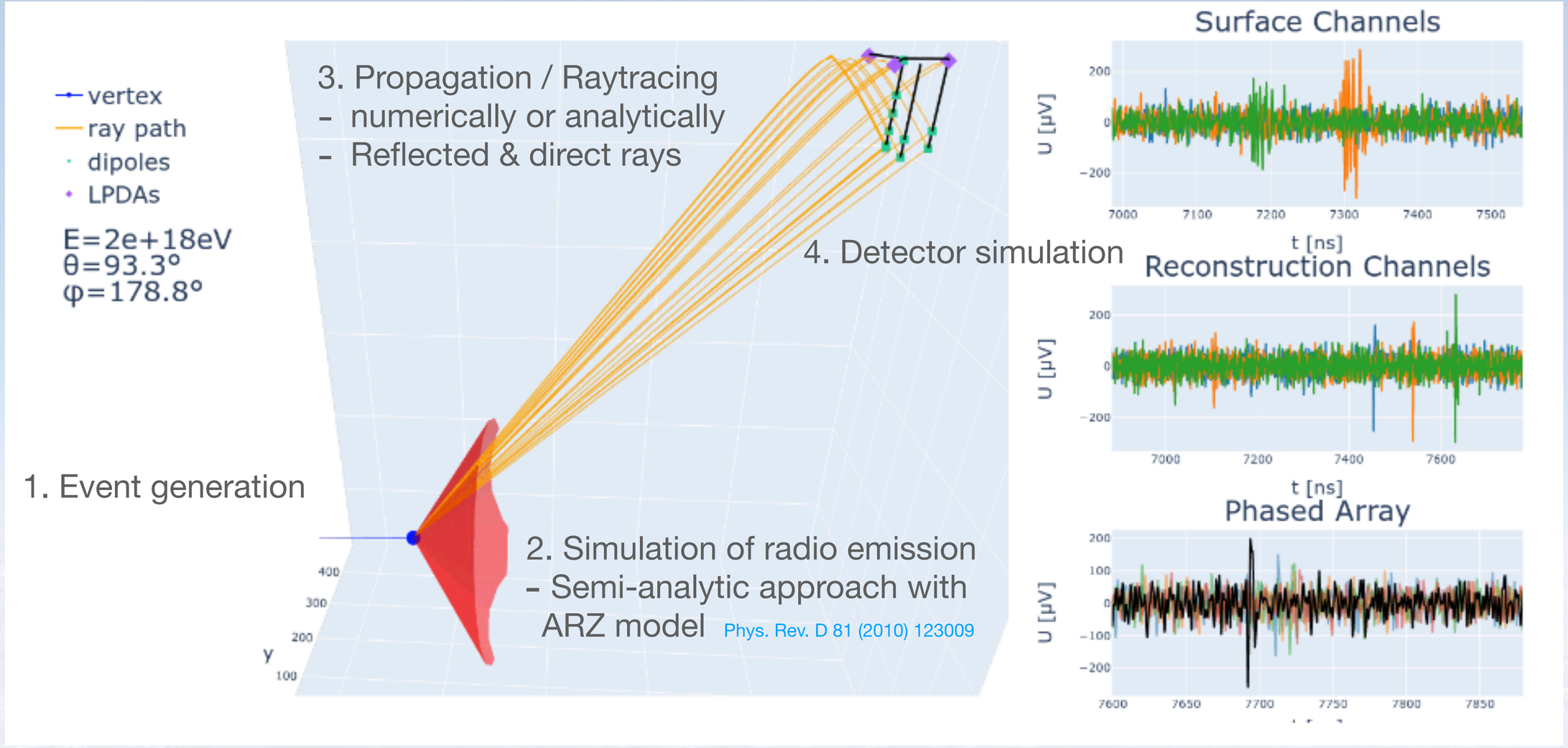
Signal polarisation reveals neutrino direction



Simulations with NuRadioMC

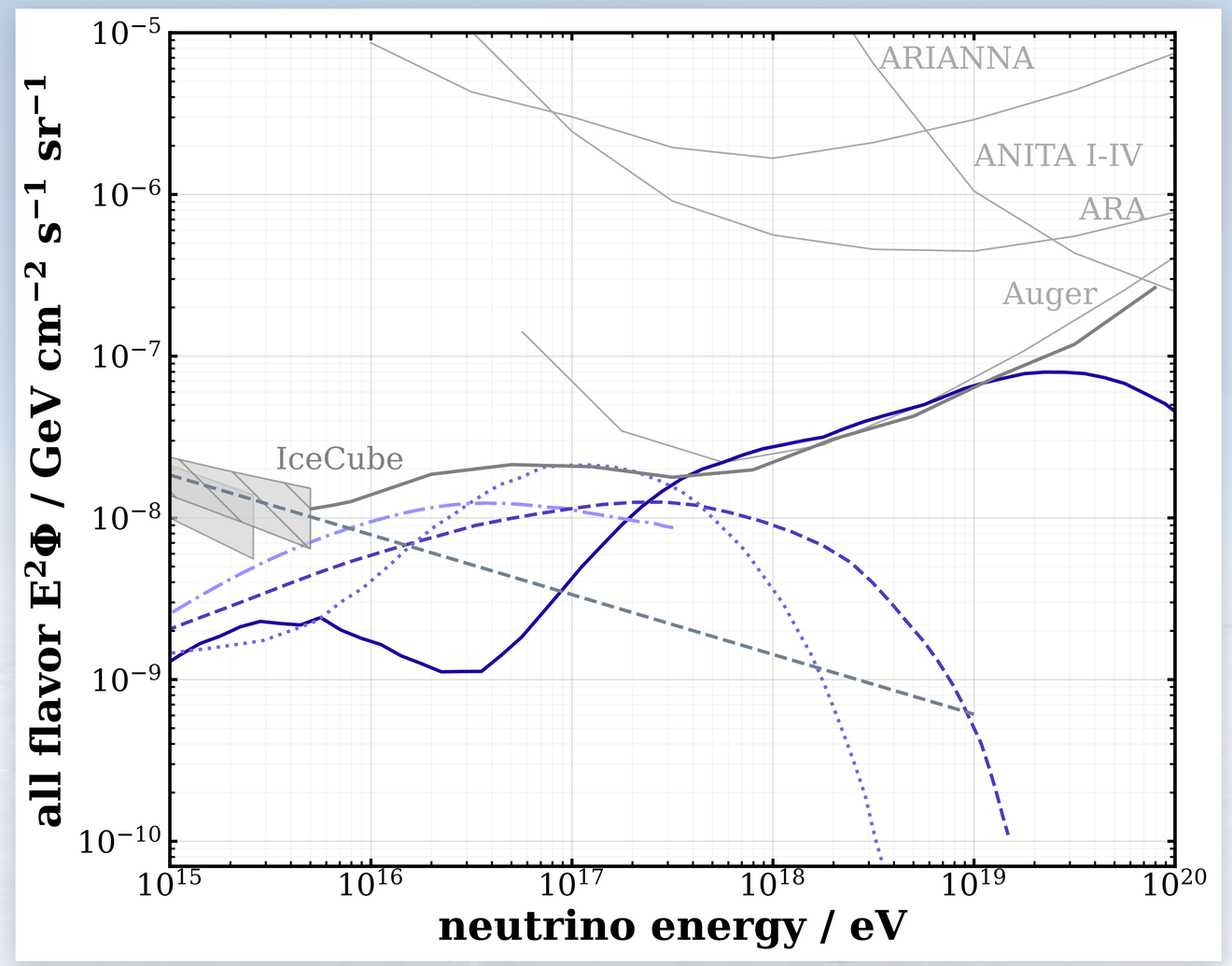
Eur. Phys. J. C 80, 77 (2020)



- Developed reconstructions
  - Energy (EPJC 82, 147 (2022)) & Arrival direction (EPJC 83 (2023) 5)
- Used to determine sensitivity (RNO-G, JINST 16 (2021) 03)

Sensitivity: Diffuse emission

- Assuming no background



M. Muzio for RNO-G, PoS (ICRC23) 1485

Sensitivity: Diffuse emission

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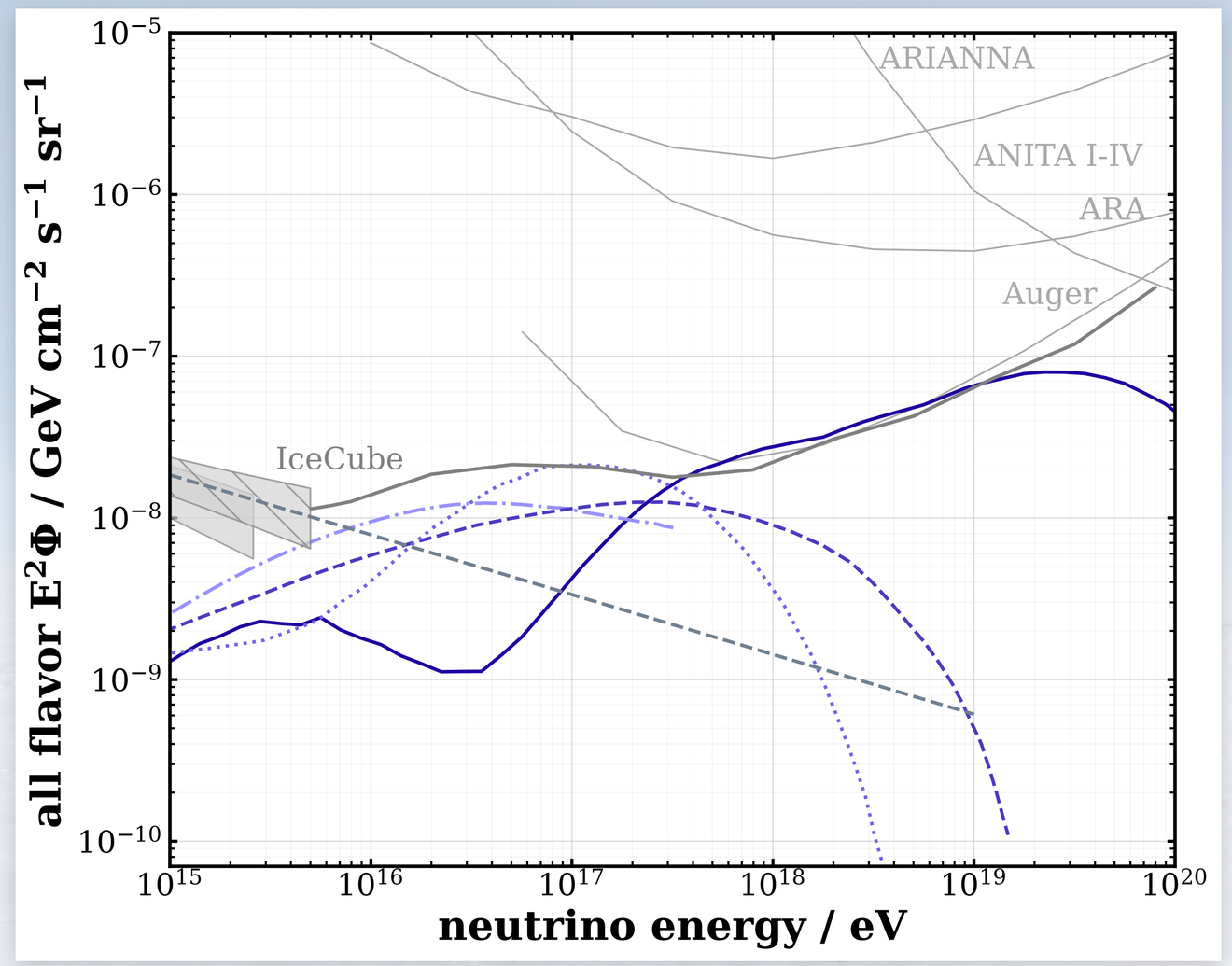
- World leading sensitivity @ 1 EeV
- Testing 2. (hard) astrophysical component



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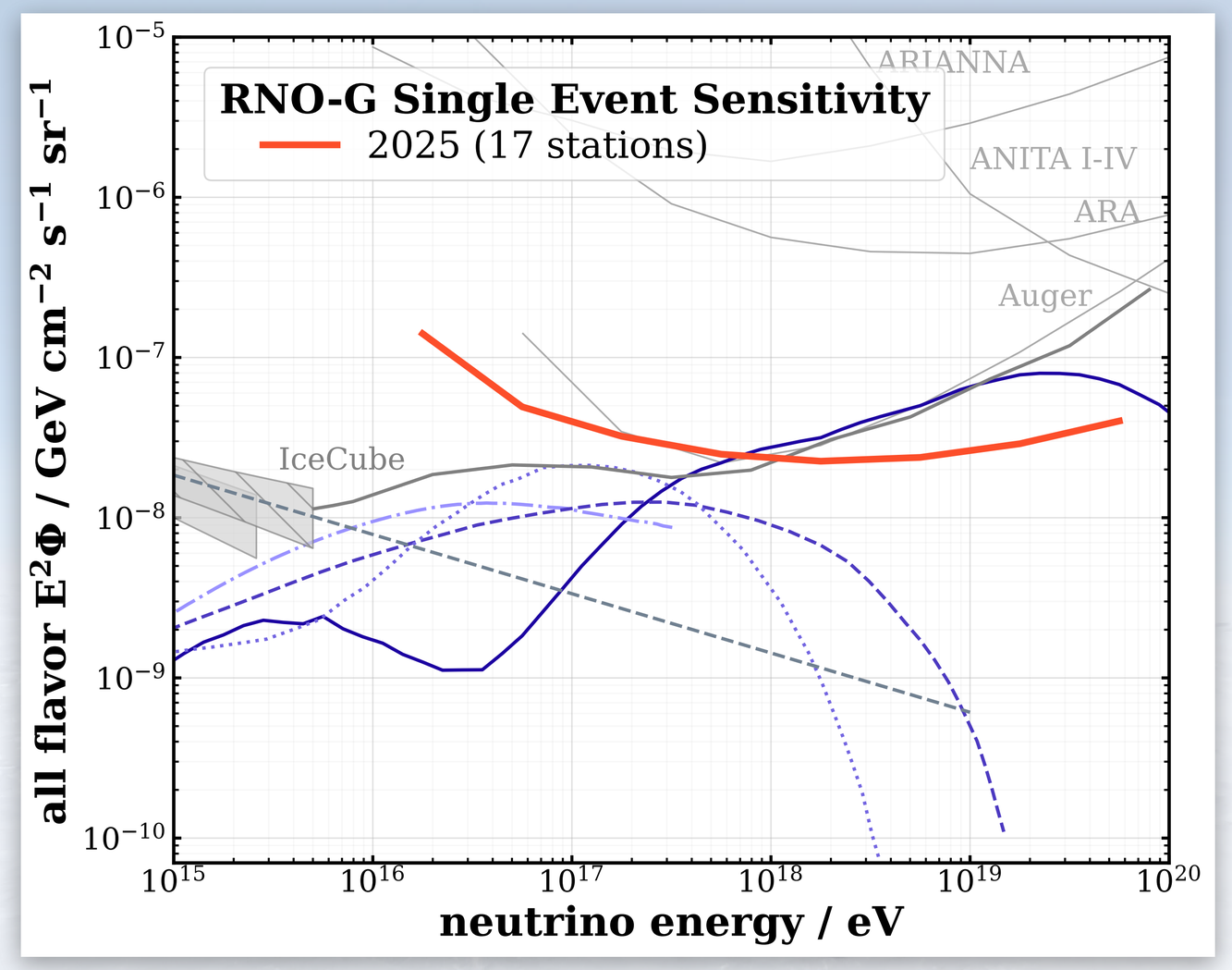

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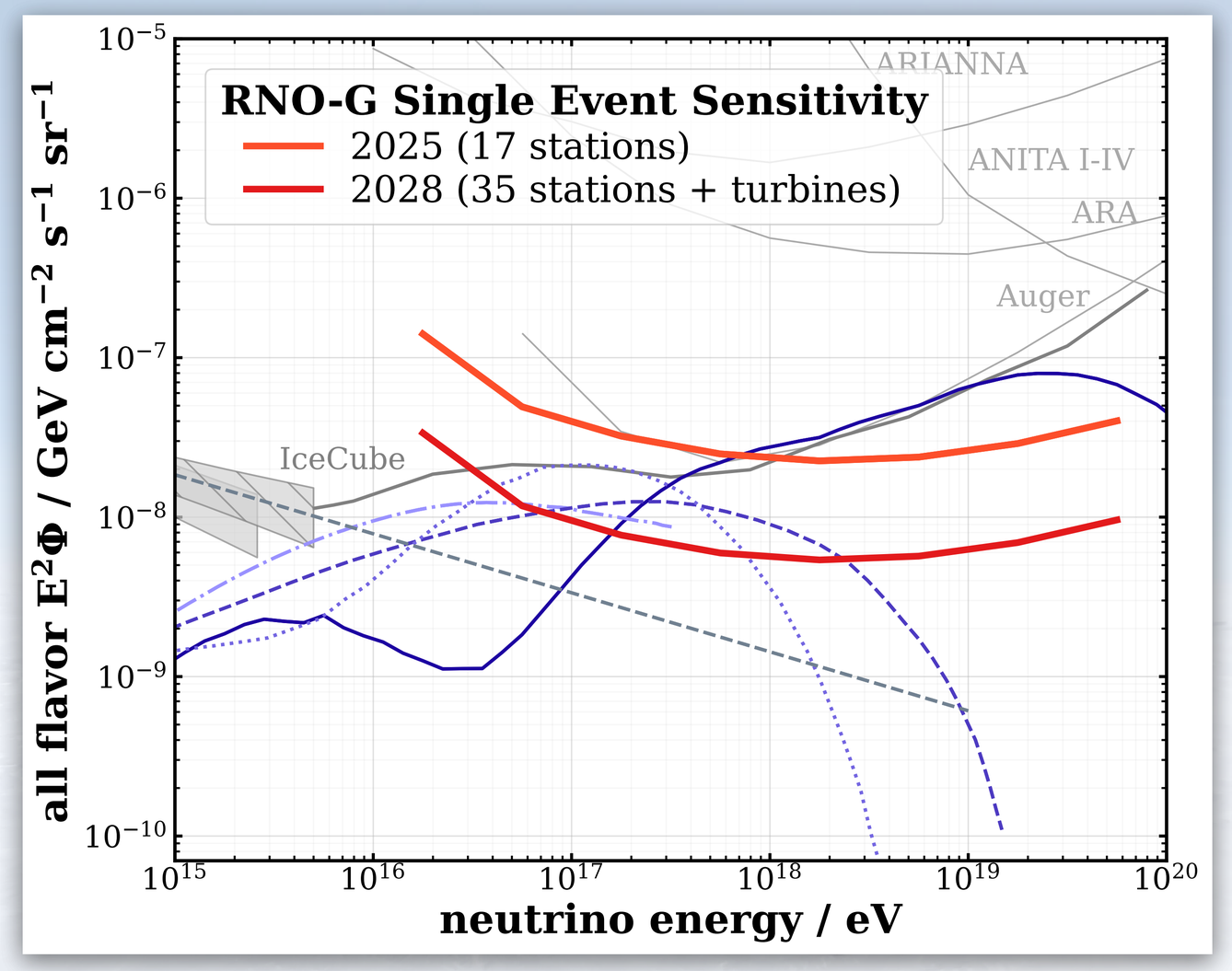

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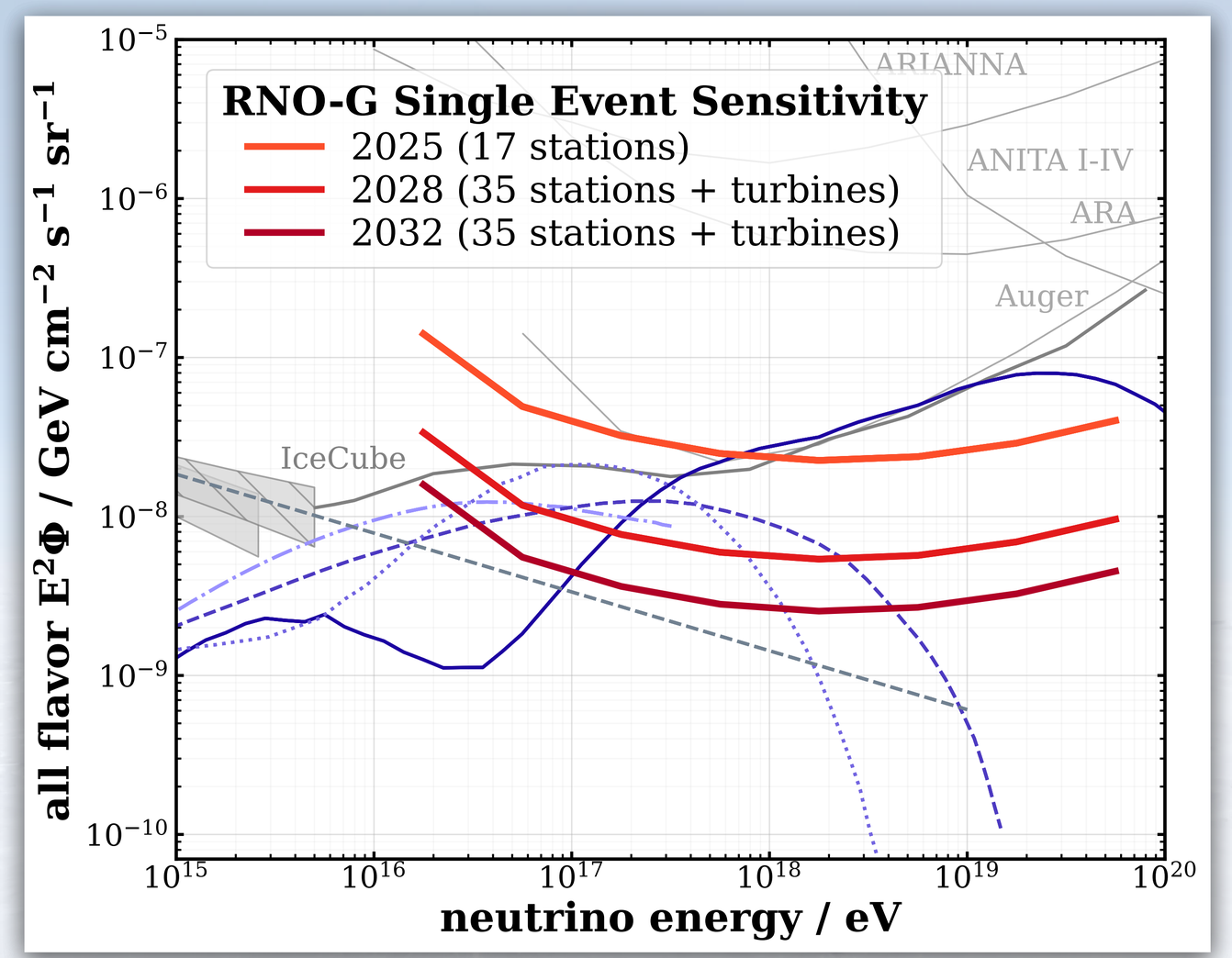

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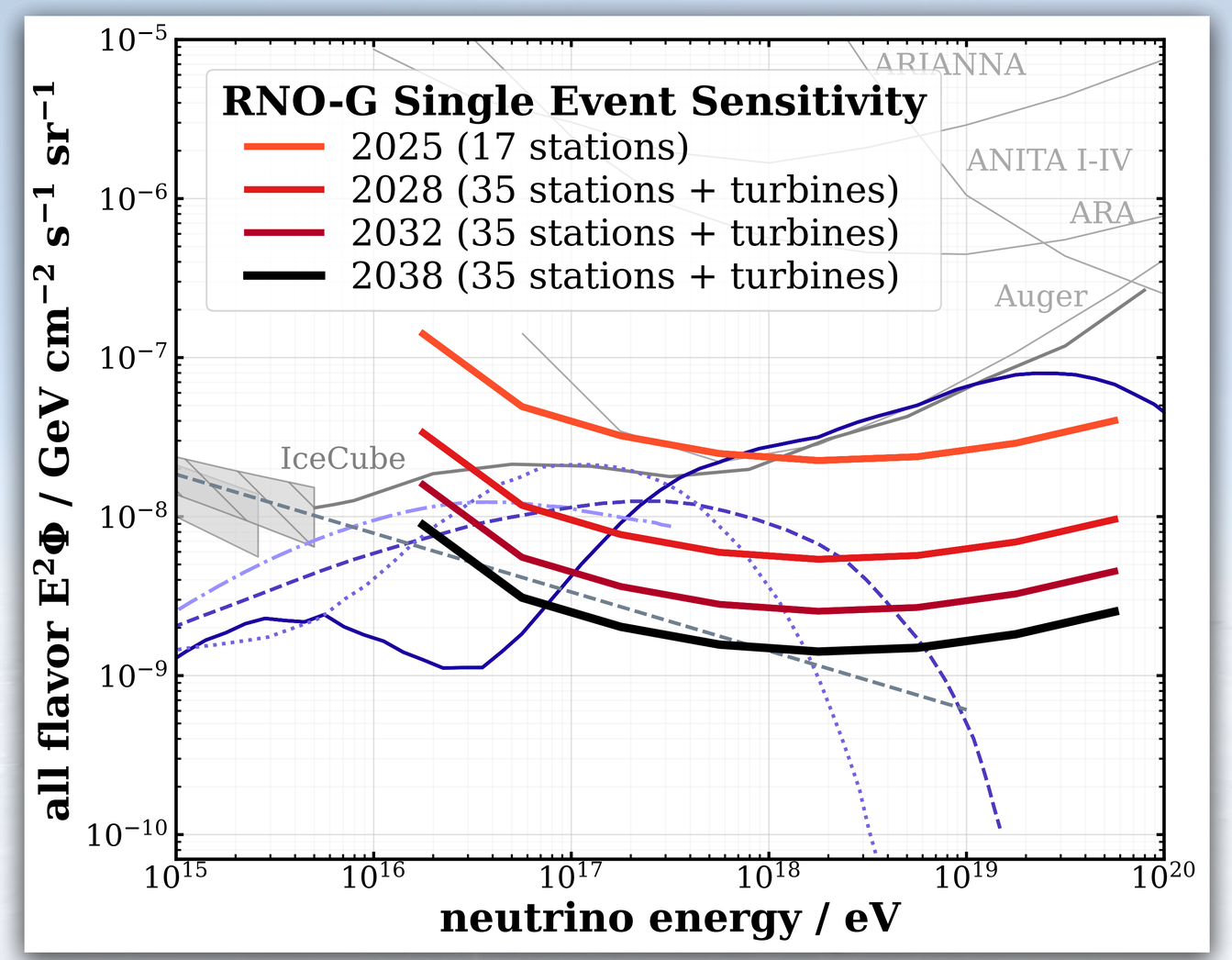
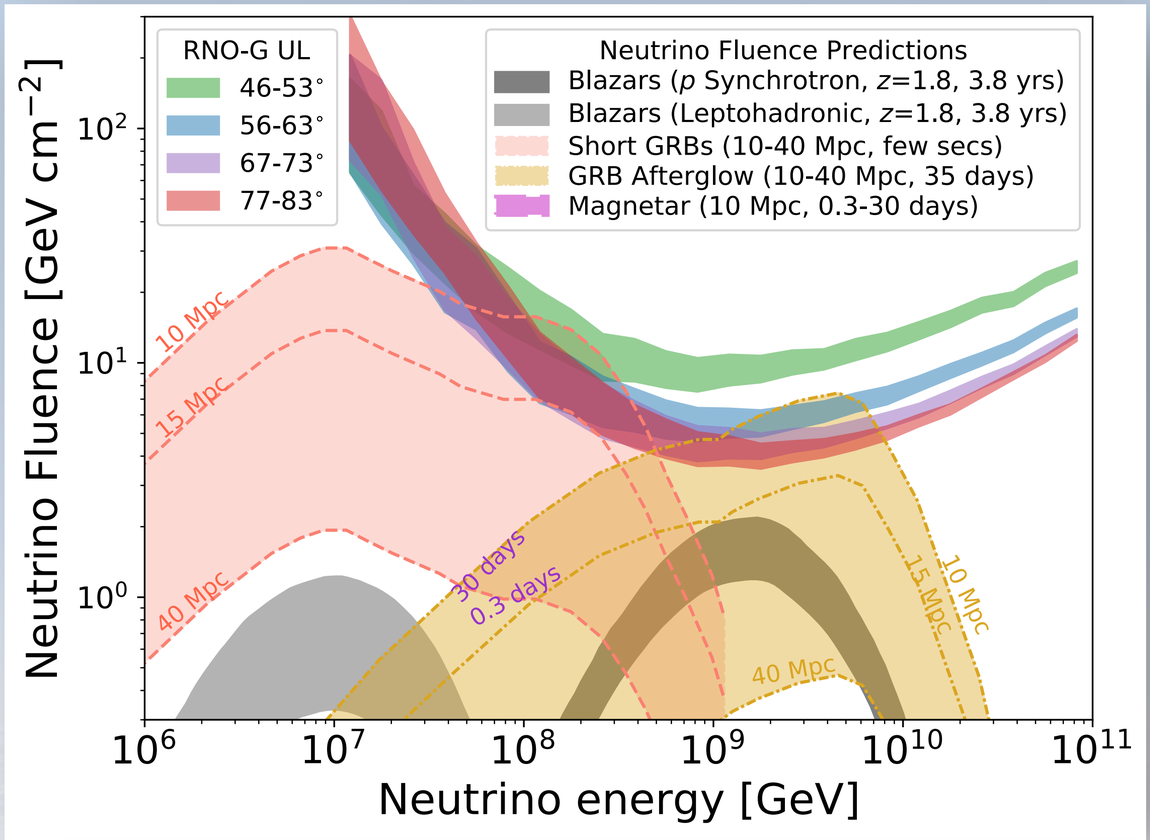


M. Muzio for RNO-G, PoS (ICRC23) 1485

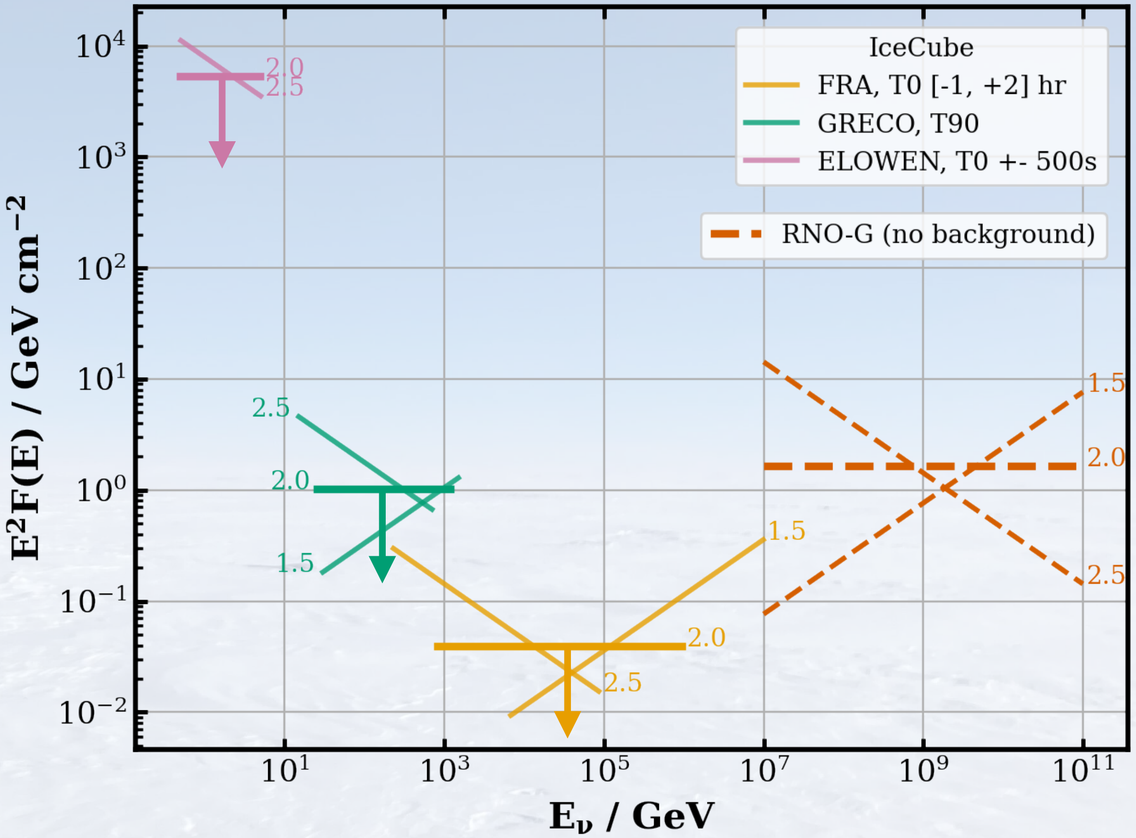
Sensitivity: Transient events



RNO-G, JINST 16 (2021) 03

- Location in Greenland very suitable for multi-messenger campaigns
- Large FOV of ~ 40 deg in zenith

Case study: RNO-G (full array) sensitivity to a particular bright GRB 221009A

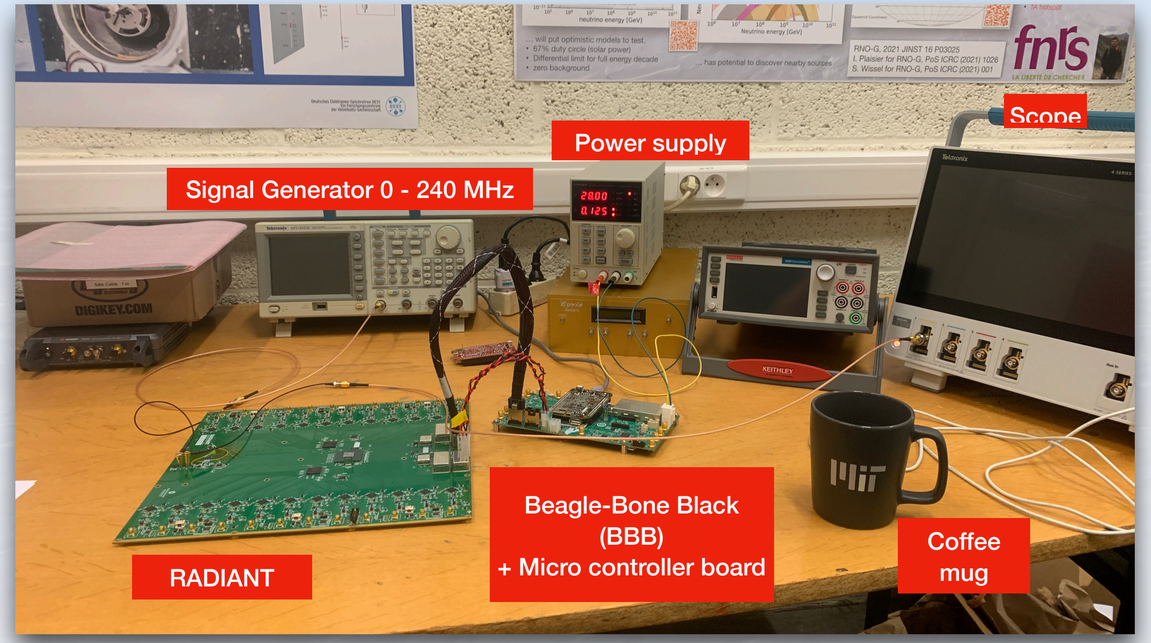


RNO-G was off not taking data at the time!

IIHE Efforts

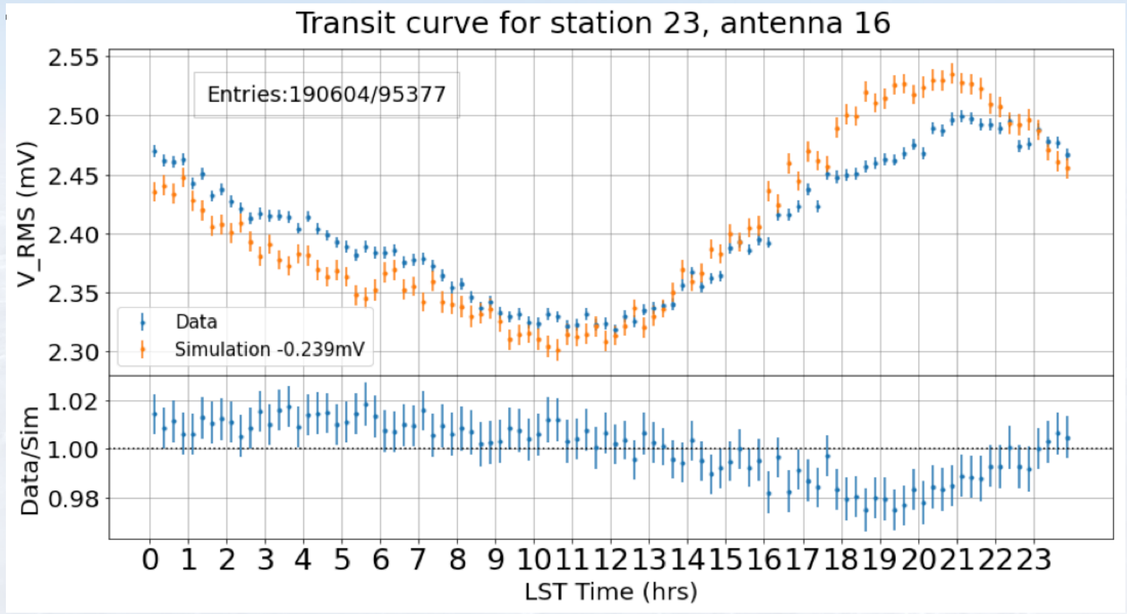
Production / Testing of Digitiser Boards

- RADIANT: 24 channel, low power, 3.2 GHz digitiser board
- Joint effort between IIHE and Desy (Germany)
- Currently producing and testing 7 boards for next season



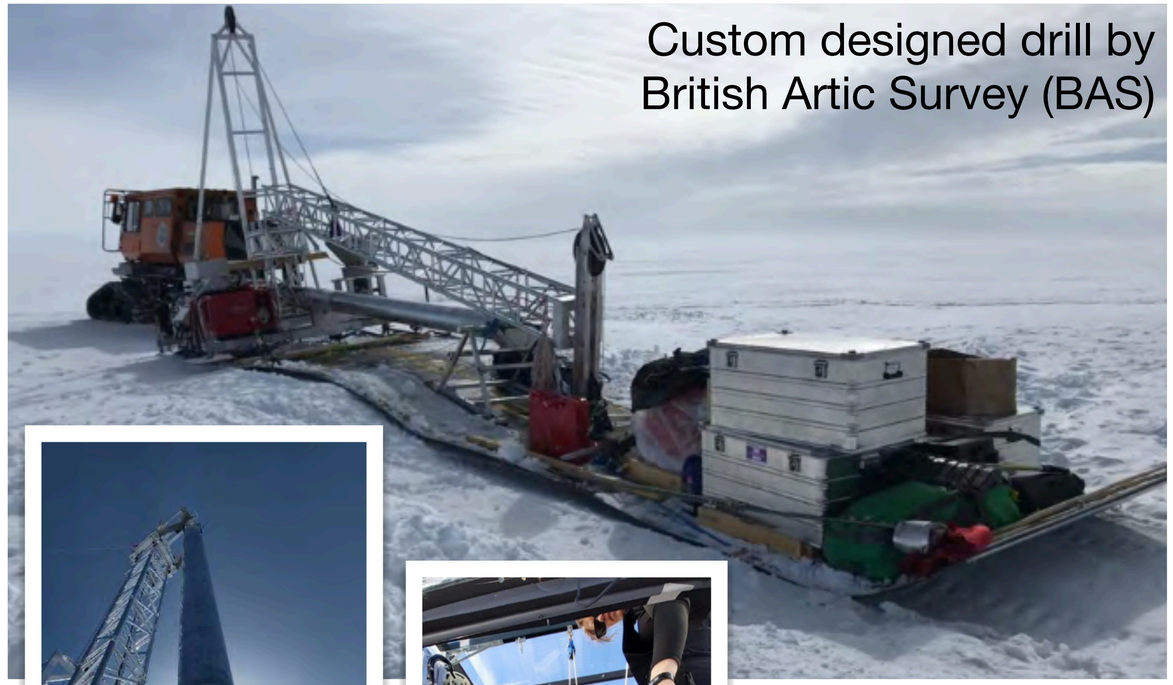
Data commissioning and calibration

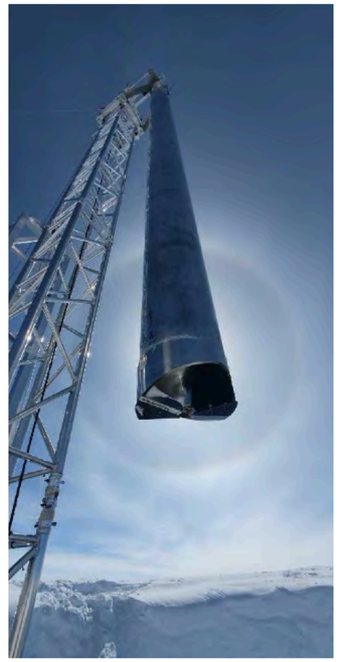
- Detecting the galactic emission with the upward facing antennas
  - Standard candle → proof of concept
  - Requires data cleaning and low-pass filtering

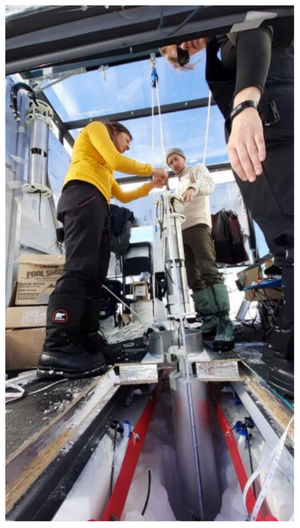


Deployment - including IIHE staff

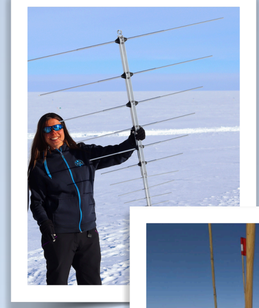
Drilling 100m deep, 28 cm diameter hole







Shallow antennas are deployed in trenches …



Next deployment season

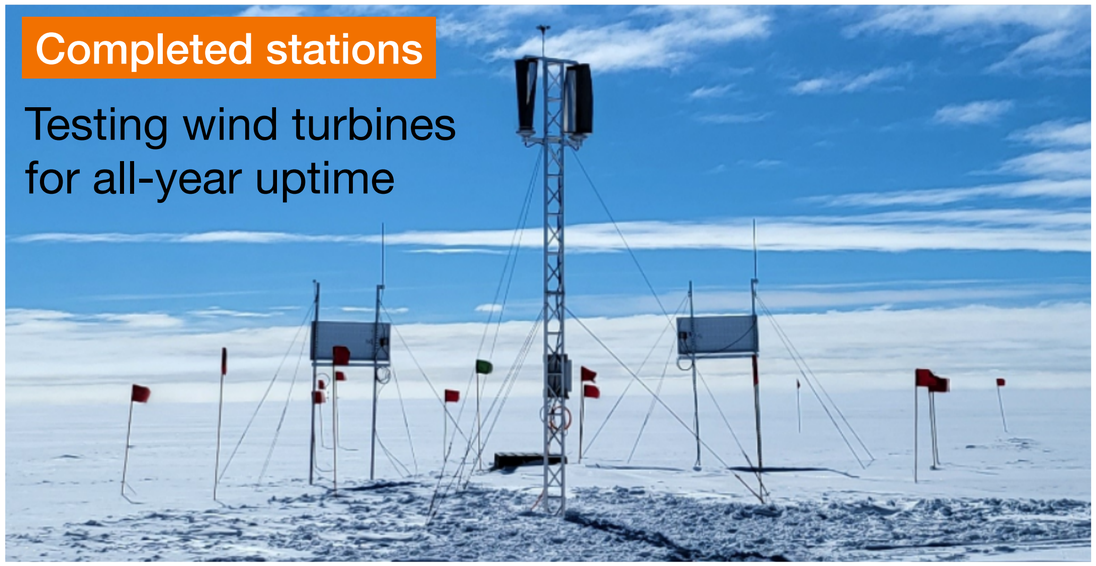
- 2 IIHE members (Me😃 and Jethro)
- 3 drilling teams, 2 deployment teams, 1 calibration team (1 month each)

- Tentative plan:
  - Installing 8+ new stations
  - Installing ~10 wind turbines (!!!)
  - Retrofitting 7 existing stations
  - Additional calibration measurements

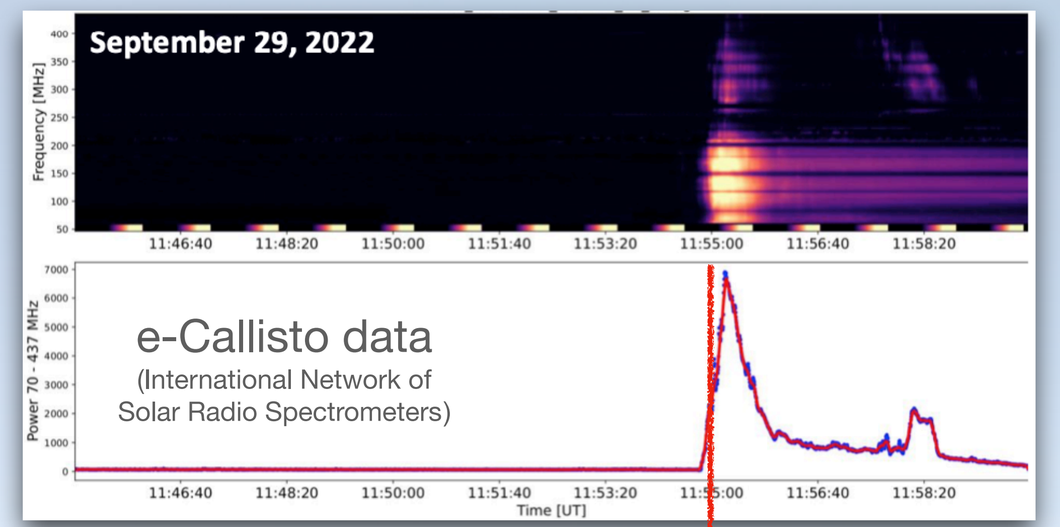
Mast climbing training

Completed stations

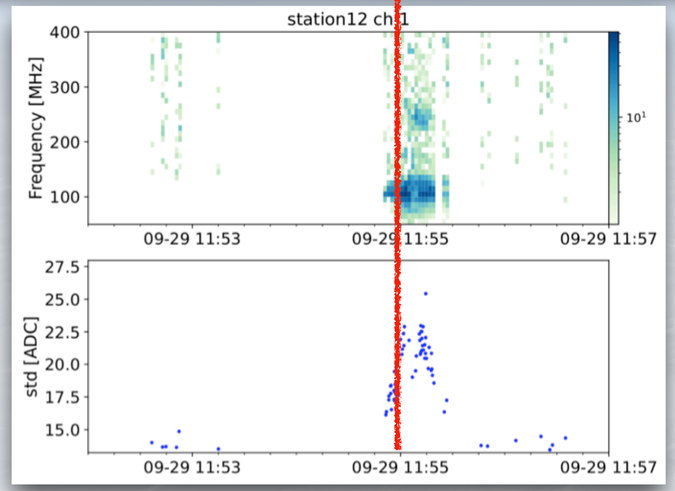
Testing wind turbines for all-year uptime



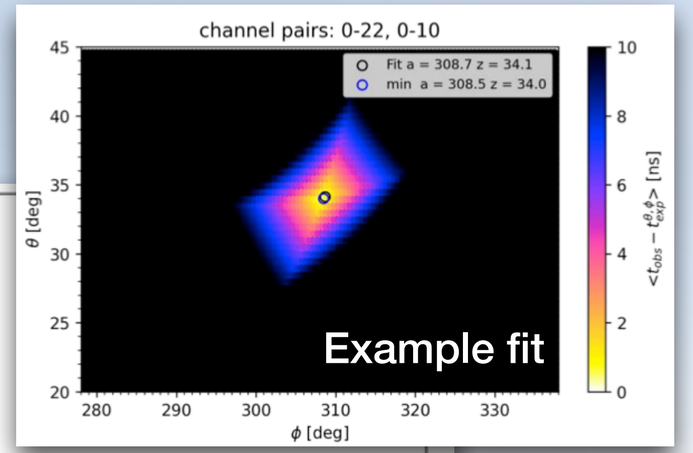
First look into the data: Solar flares

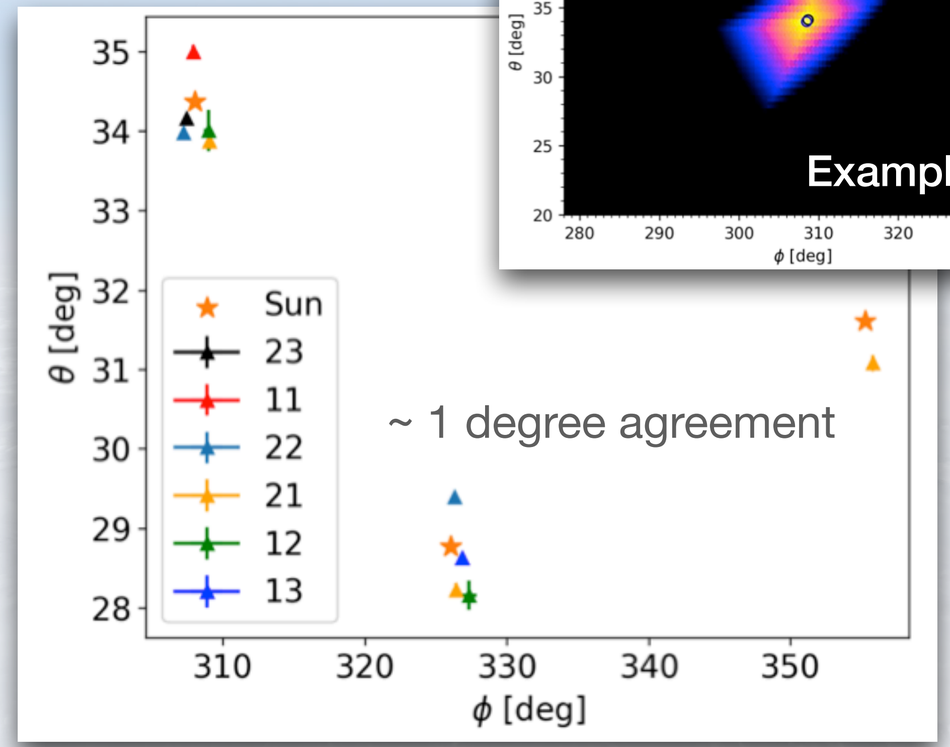


RNO-G data:



- For 3 solar flares, reconstruct position of Sun
- Allowed correction / calibration of station geometry





Summary

- 7 station already in operation in Greenland; Fully funded for in total 35 stations
- RNO-G will have world leading sensitivity for 1 EeV neutrinos
  - Potential to discover the first UHE neutrino!
- RNO-G observes northern sky for UHE neutrinos complementary to IceCube

- Contributing from IIHE to various activities:
  - Data analysis (Neutrino searches, ….)
  - Hardware production & testing
  - Data commissioning & Deployment support

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Picture by Ben Young

Whittier College
Summit Station
Uppsala University
DESY-Zeuthen
FAU-Erlangen
Radboud University
Université Libre de Bruxelles
Vrije Universiteit Brussels
Ghent University
University of Nebraska-Lincoln
University of Kansas
University of Wisconsin-Madison
University of Chicago
The Ohio State University
Pennsylvania State University
University of Alabama
University of Delaware
University of Maryland

RNO-G
Collaboration
February 2023

THE UNIVERSITY OF CHICAGO
WISCONSIN UNIVERSITY OF WISCONSIN-MADISON
VUB VRIJE UNIVERSITEIT BRUSSEL
ULB UNIVERSITÉ LIBRE DE BRUXELLES
DESY.
FAU Friedrich-Alexander-Universität Erlangen-Nürnberg
KU THE UNIVERSITY OF KANSAS
PennState
THE OHIO STATE UNIVERSITY
THE UNIVERSITY OF ALABAMA
UNIVERSITY OF MARYLAND
WHITTIER 1887 COLLEGE
GHENT UNIVERSITY
UNIVERSITY OF DELAWARE
UPPSALA UNIVERSITET
Radboud University
UNIVERSITY OF Nebraska Lincoln

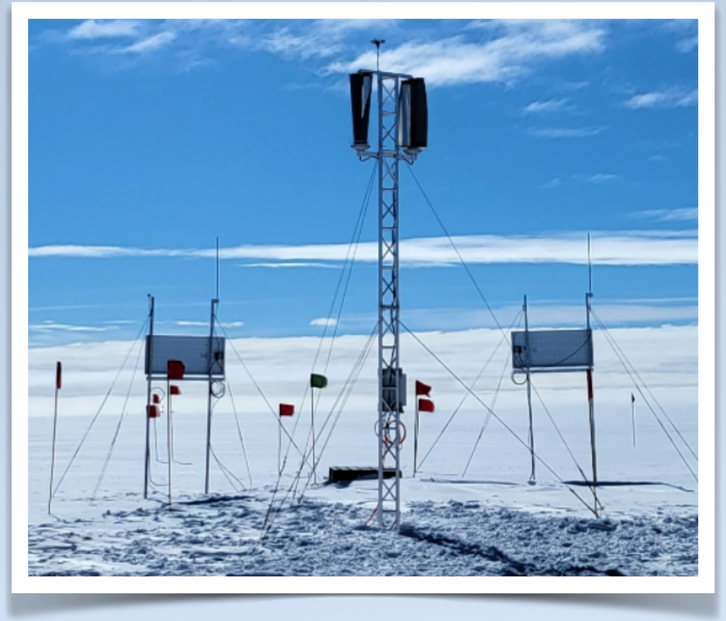
IIHE Efforts: Other tasks

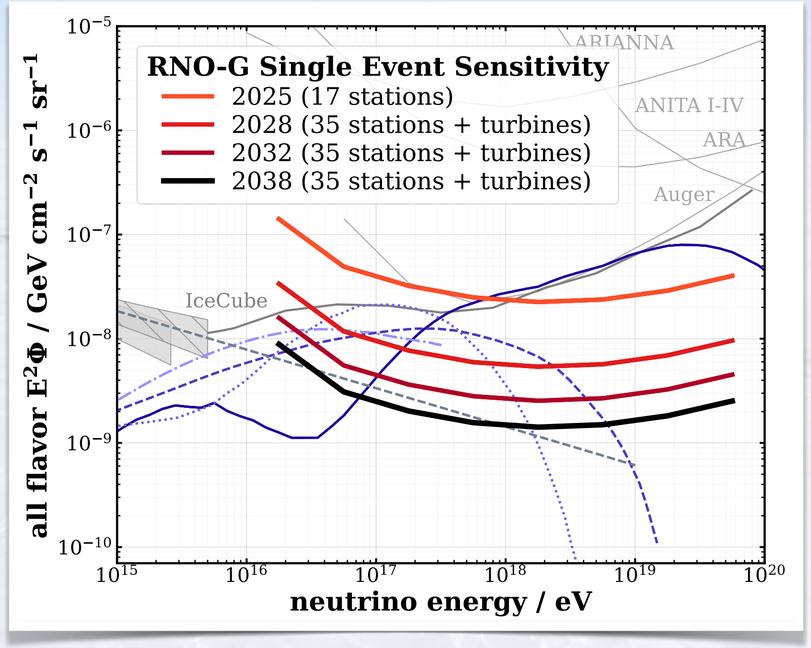
- Data commissioning
- Coding
- Voltage calibration
- ....

Backup

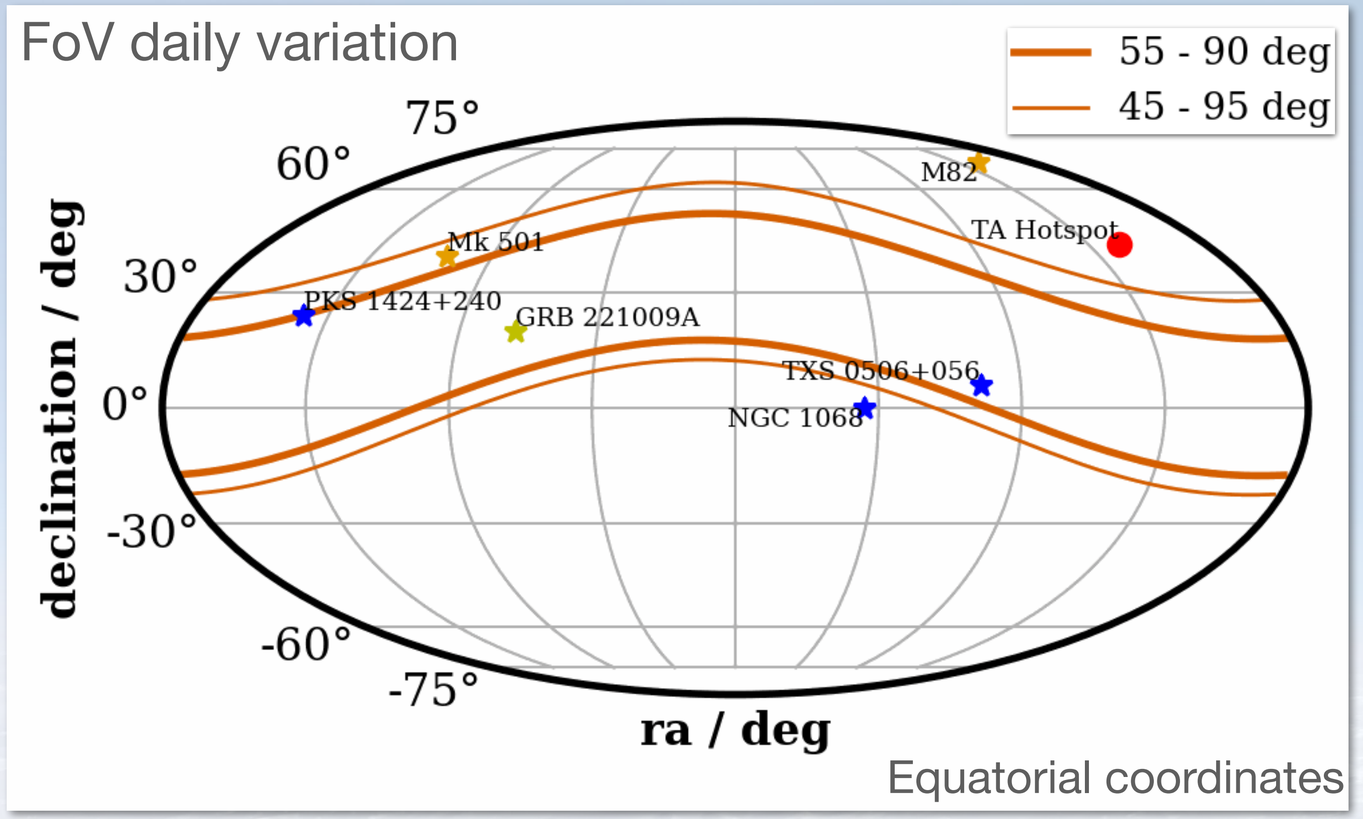
Summary & Outlook

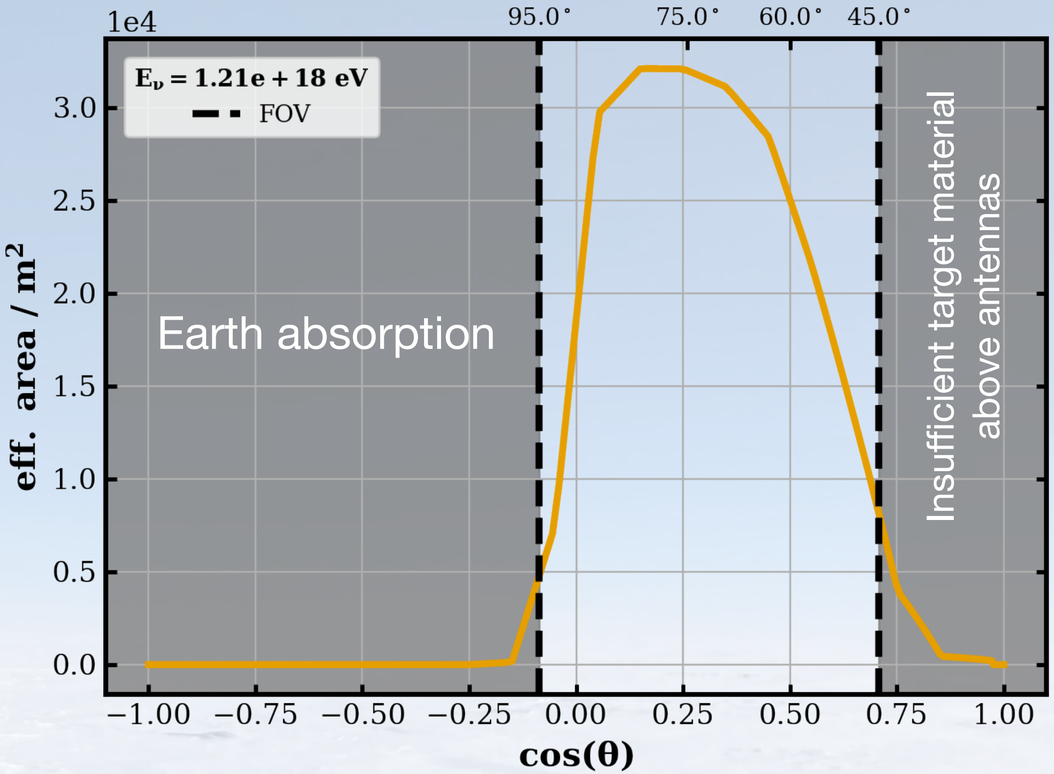
- RNO-G is currently deploying at Summit Station in Greenland
- When completed, RNO-G will have world leading sensitivity for 1 EeV neutrinos
  - Potential to discover the first UHE neutrino!
- RNO-G will be contributing with UHE neutrino observation to multi-messenger campaigns in the Northern Hemisphere
- Current efforts focus on calibration & commissioning
- We are preparing for neutrino searches!
  - Developing a rapid follow up analysis
  - We have developed reconstruction algorithms
  - 10 contributions at ICRC23





Neutrinos from the northern sky





- Earth is opaque for UHE neutrinos
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- RNO-G eff. area for full 35 station array
- Largest aperture just above the horizon

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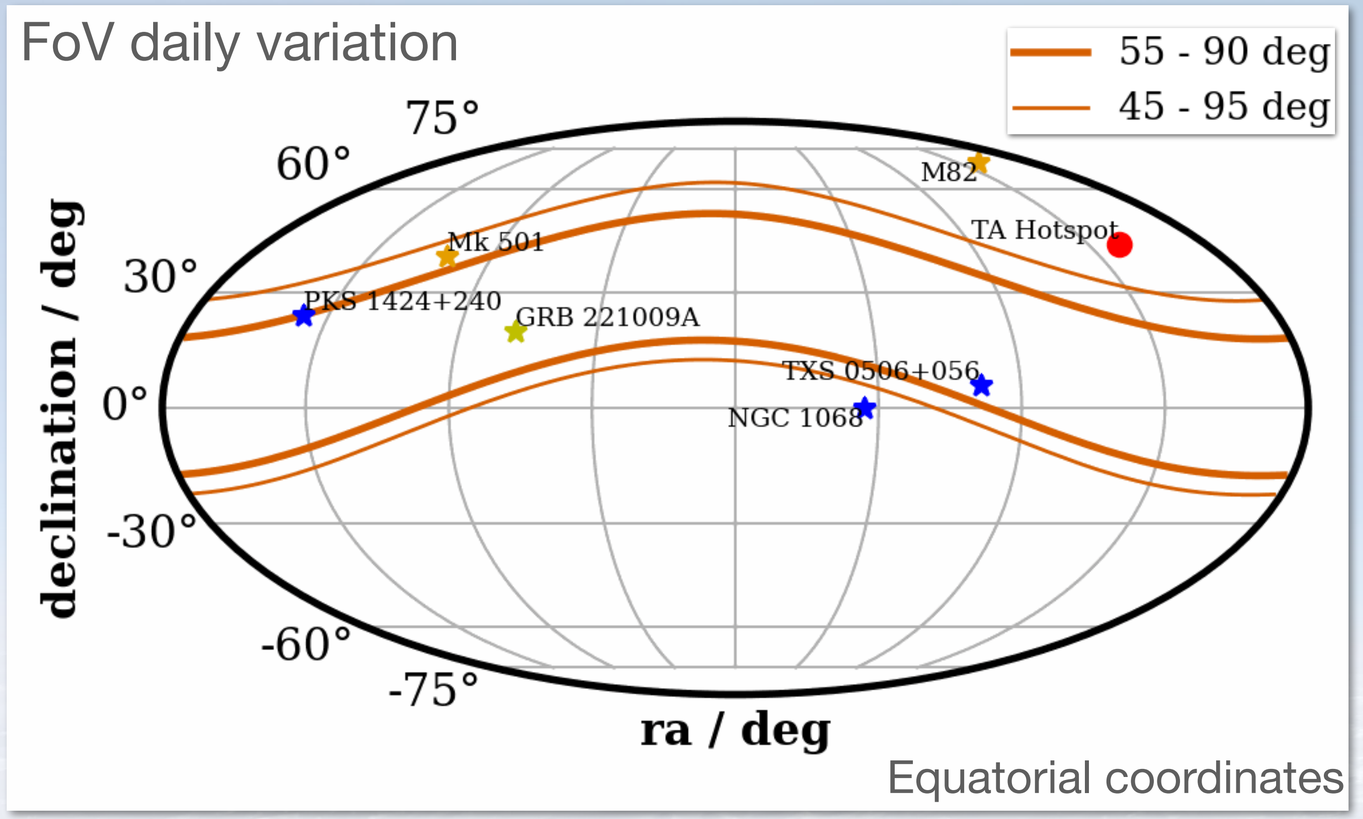

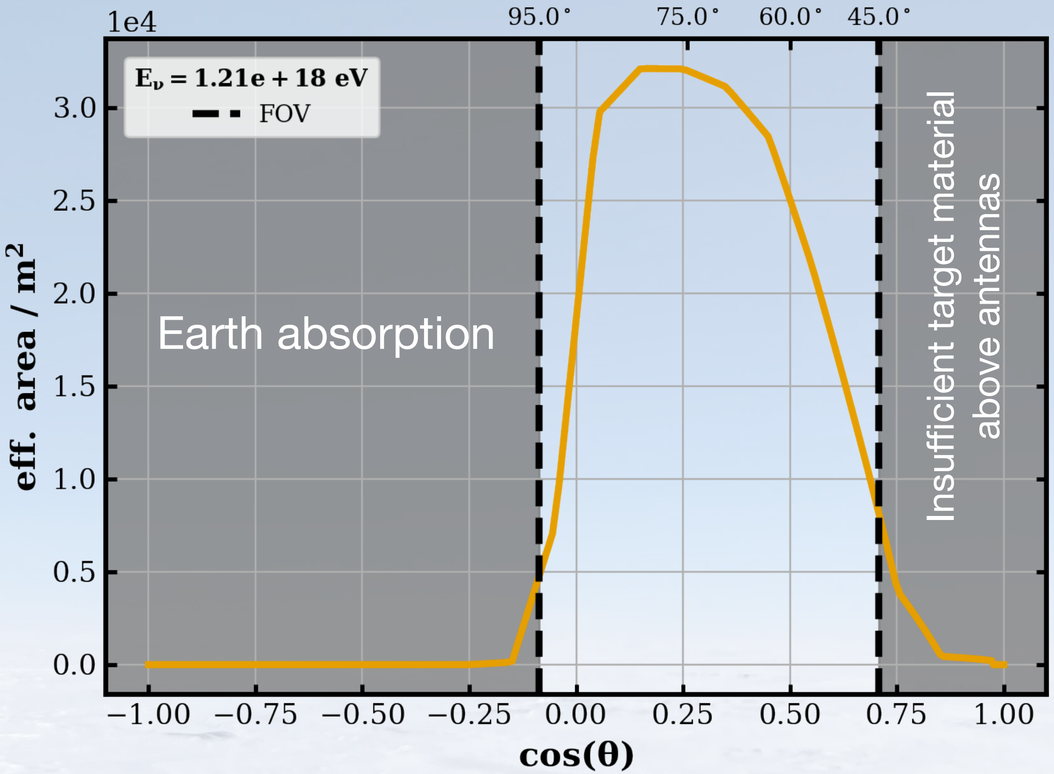

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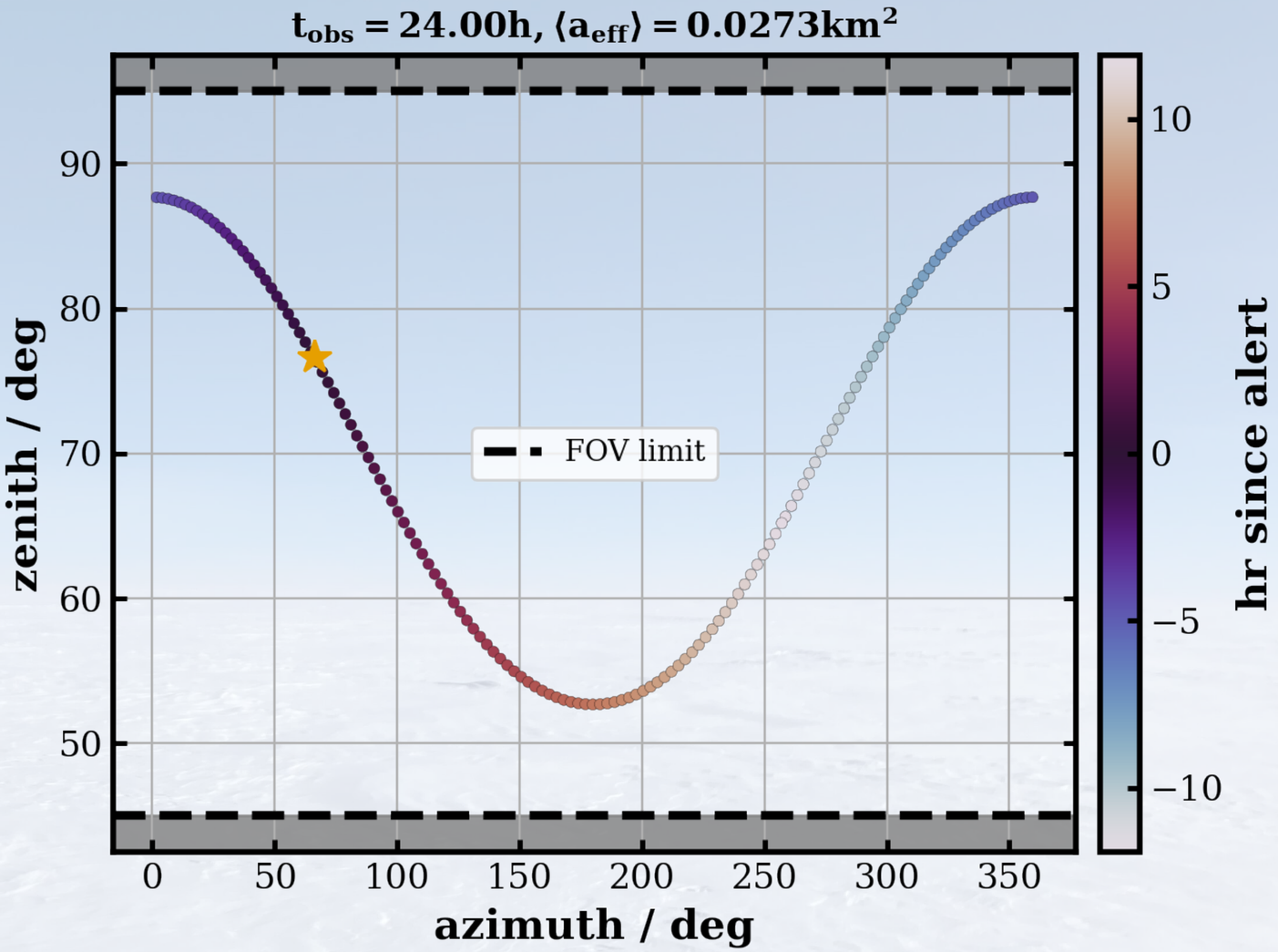
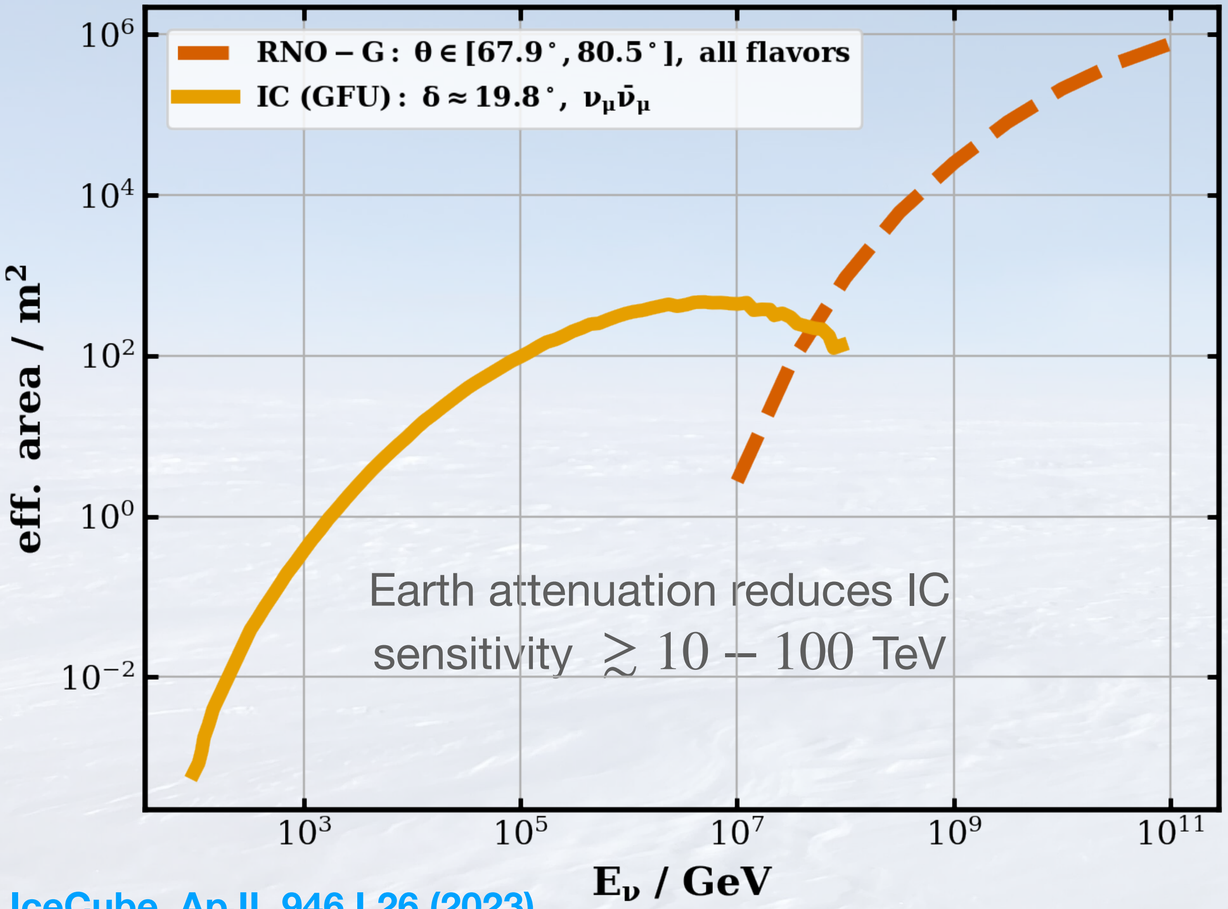
GRB 20221009A in the FOV of RNO-G

- Extremely bright GRB
- Detector was off (winter mode) at that time!
  - But what if!
- Perfectly in FOV of RNO-G
  - 24h visible, alert at favourable zenith angle band 70 - 80 deg



Sensitivity: GRB 20221009A

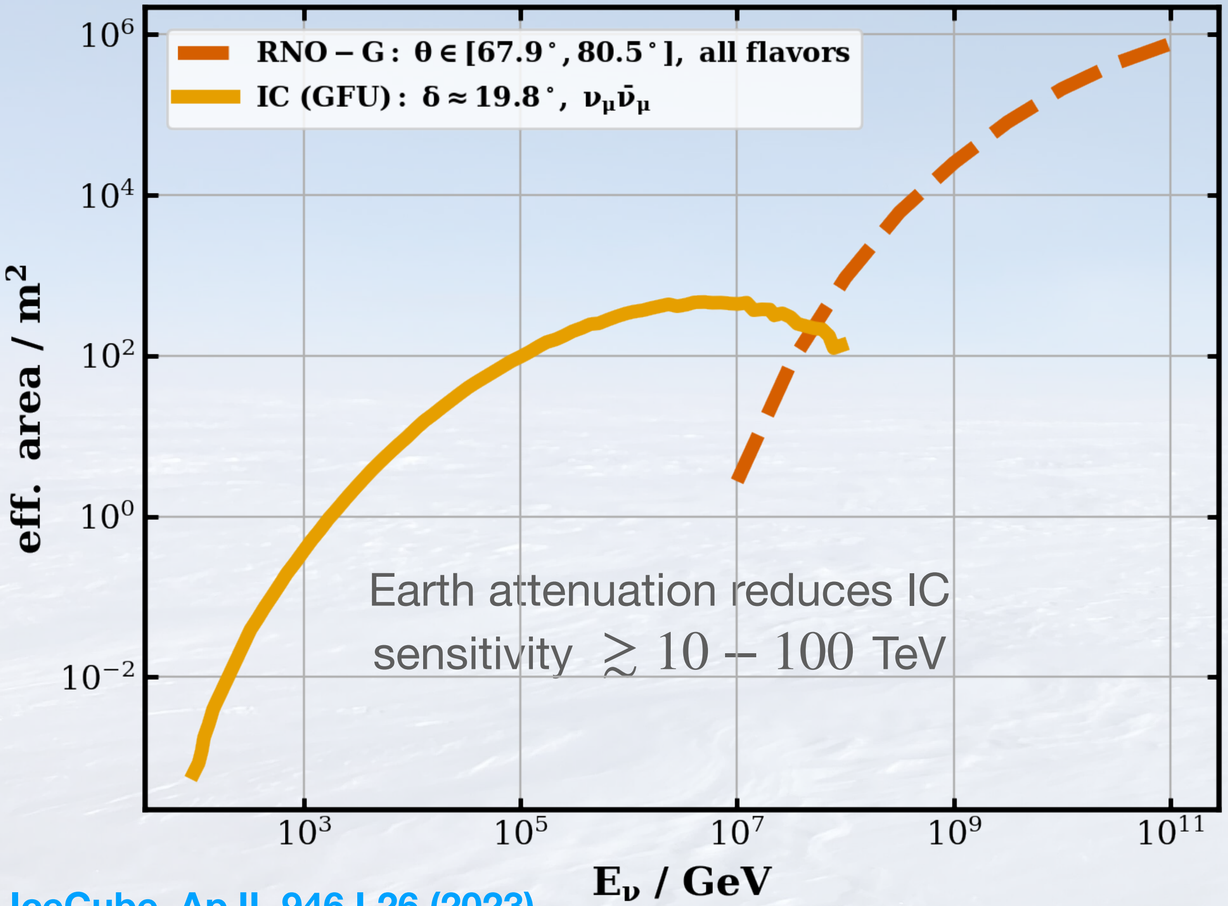
- RNO-G eff. area for 3h time window

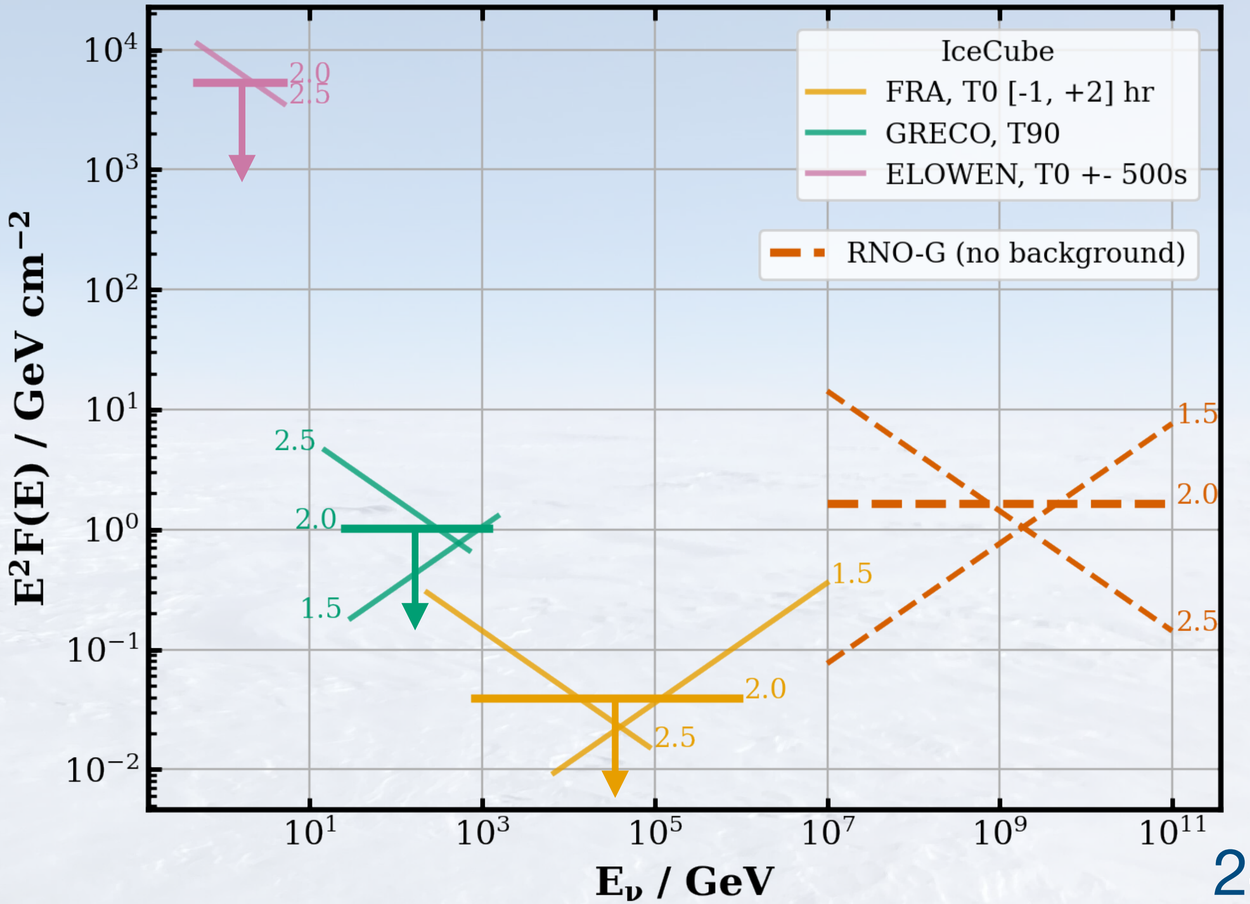


IceCube, ApJL 946 L26 (2023)

Sensitivity: GRB 20221009A

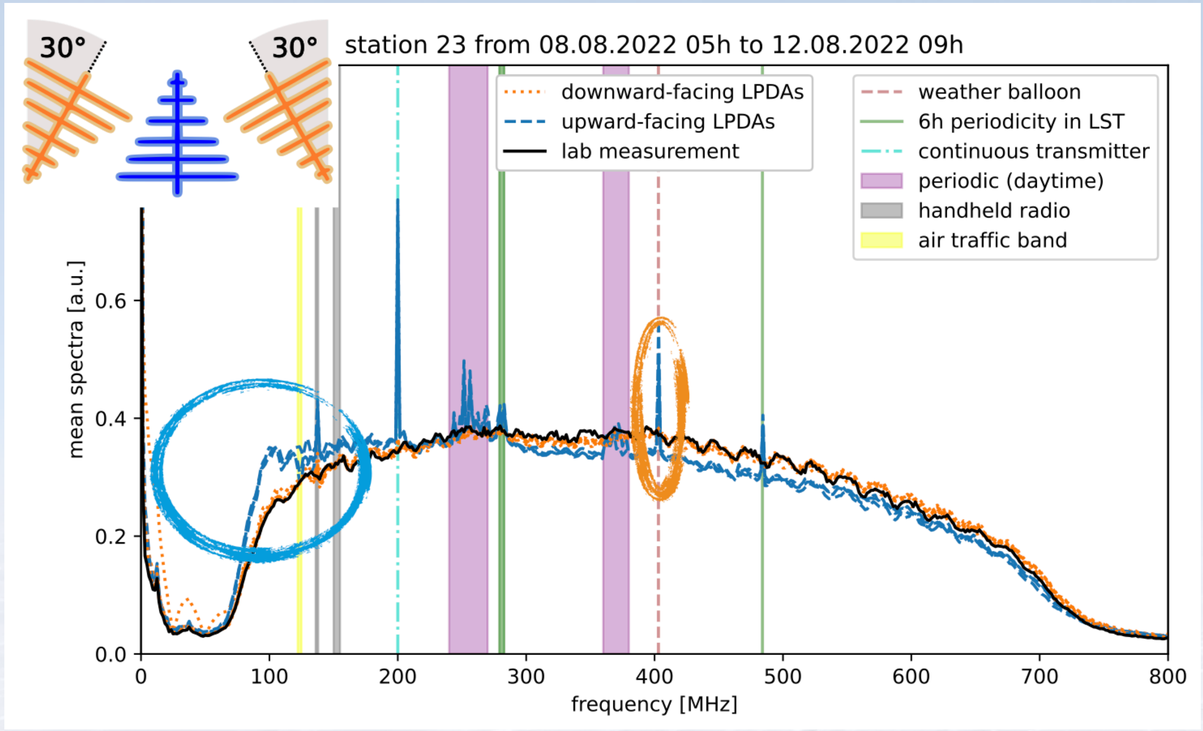
- RNO-G eff. area for 3h time window
- Sensitivity on time integrated E^{-2} flux over several decades in energy
  - RNO-G with competitive sensitivity at higher energies





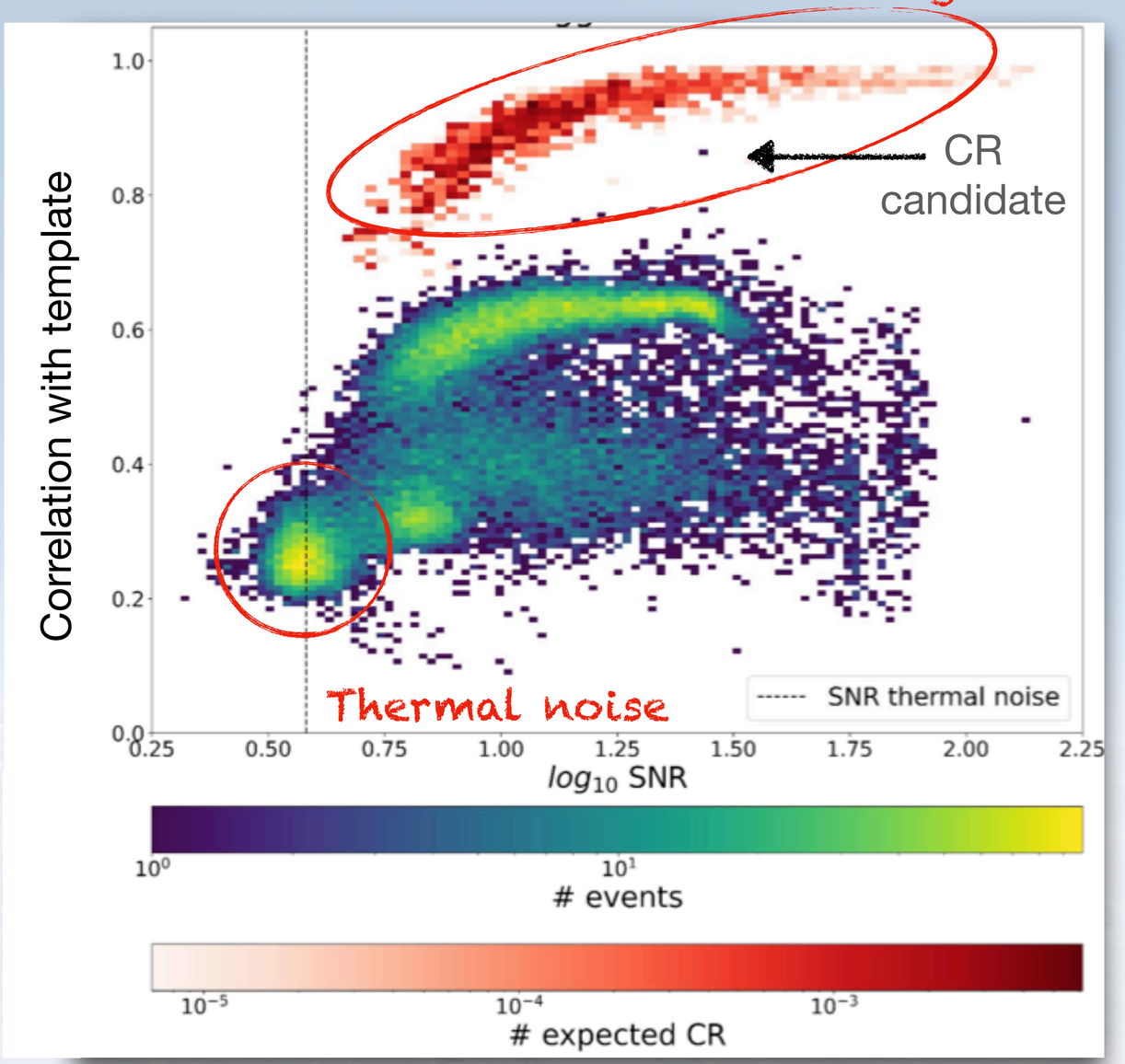
IceCube, ApJL 946 L26 (2023)

First look into the data



Excess in received power at lower frequencies for upward-facing LPDAs → Galactic emission

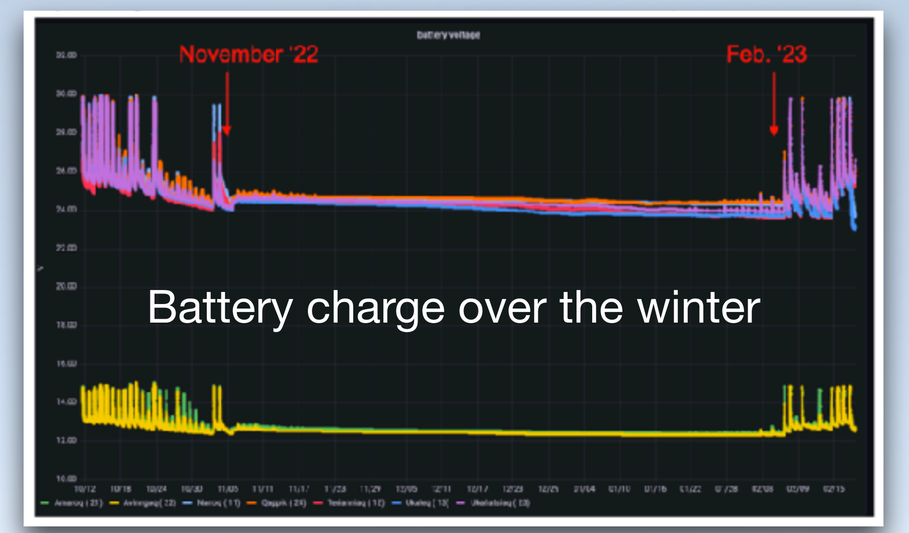
Simulated CR signals

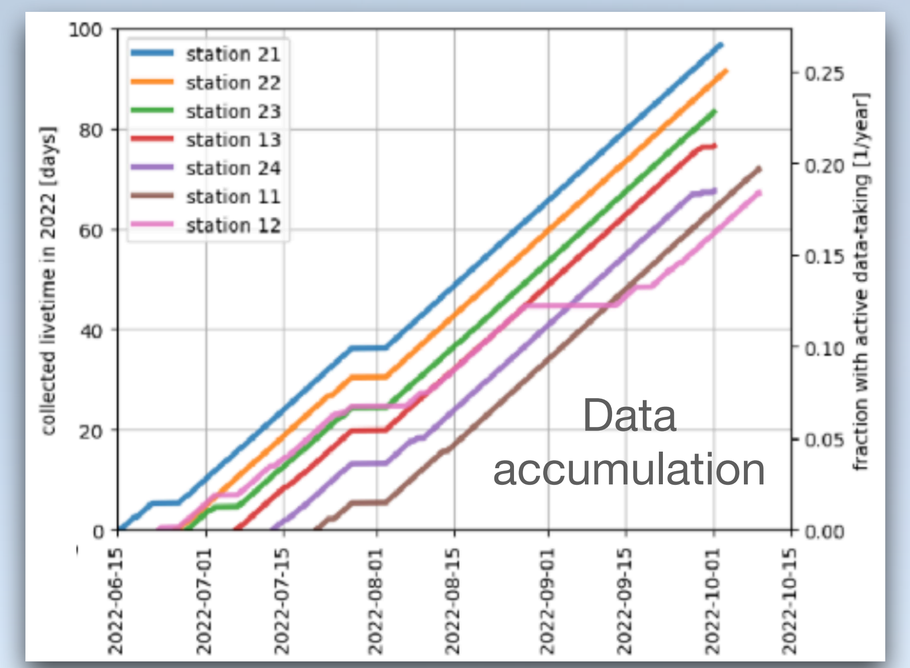


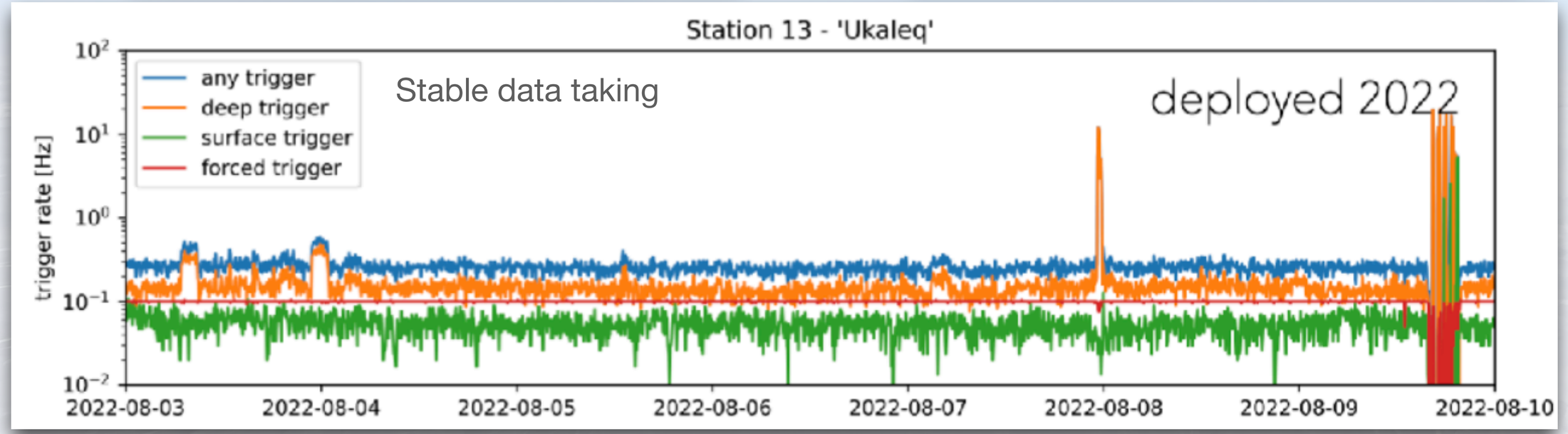
[S. Hallmann for RNO-G, Pos (ICRC23) 1043]

[J. Henrichs and A. Nelles for RNO-G, Pos (ICRC23) 259]

Hardware performance

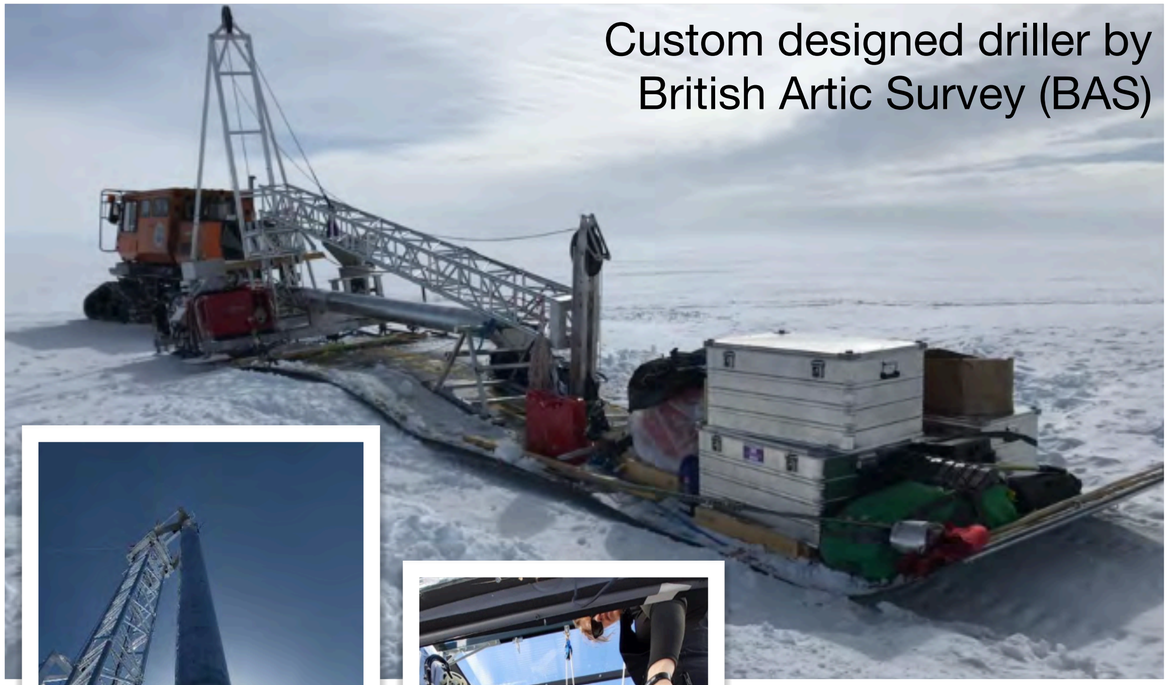


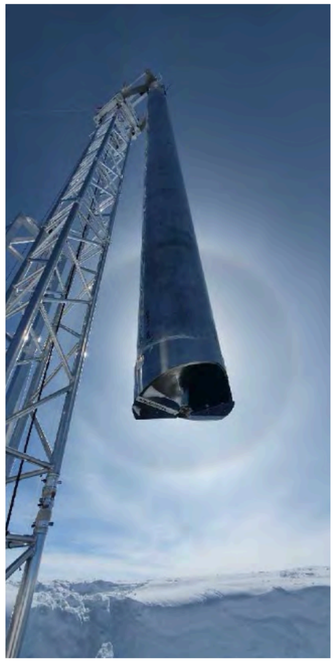


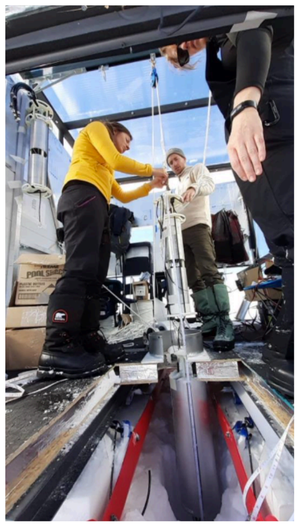


Deployment

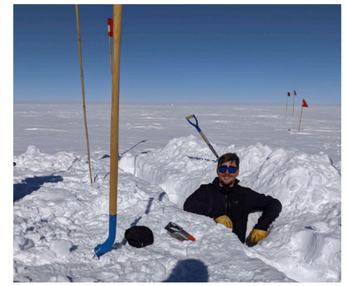
Drilling 100m deep, 28 cm diameter hole





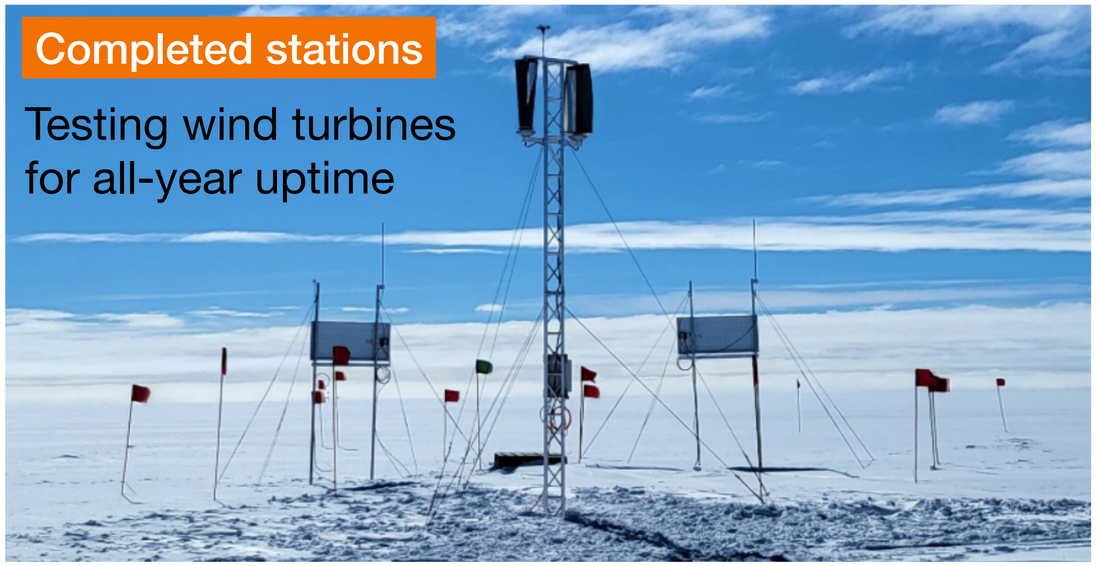


Shallow antennas are deployed in trenches …



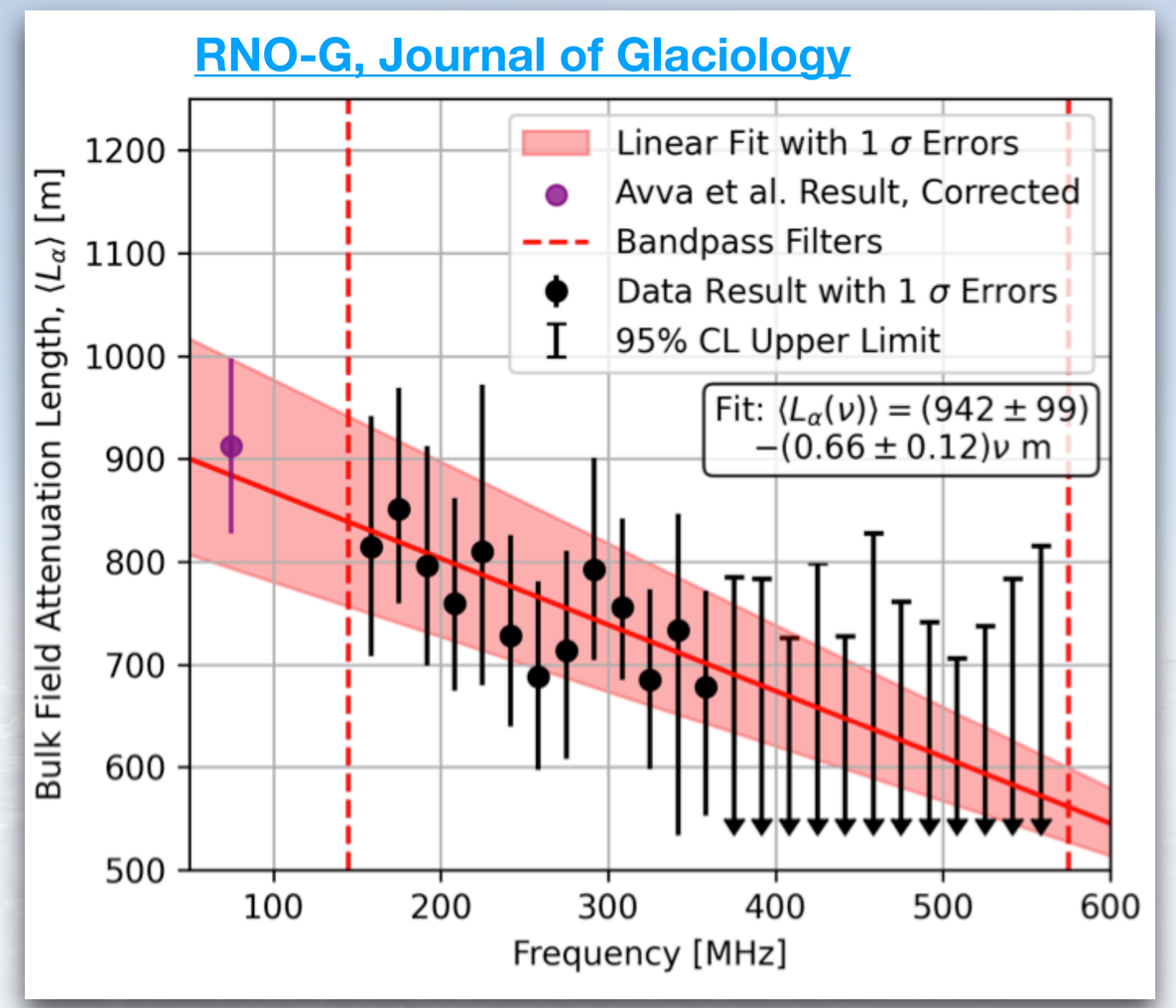
Completed stations

Testing wind turbines
for all-year uptime



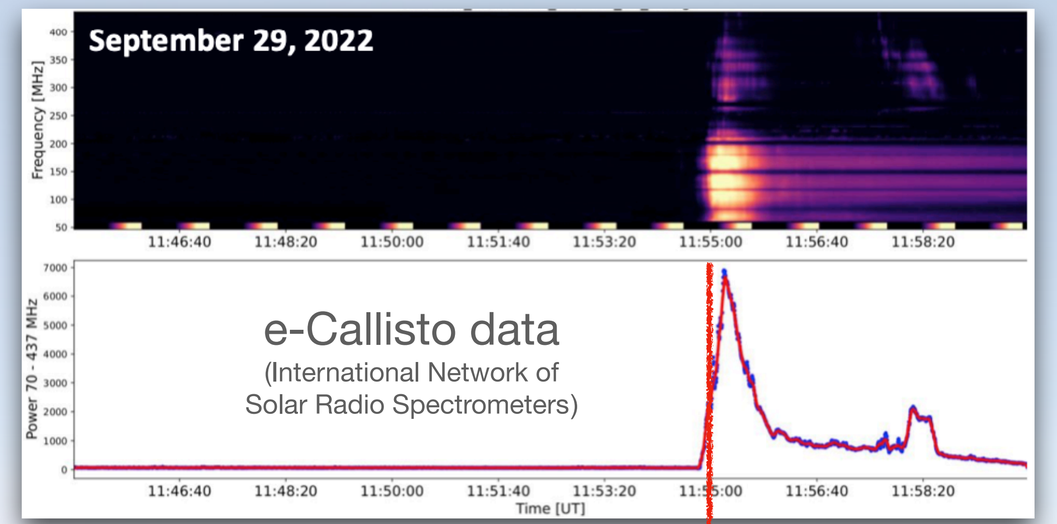
Radio detection of neutrinos

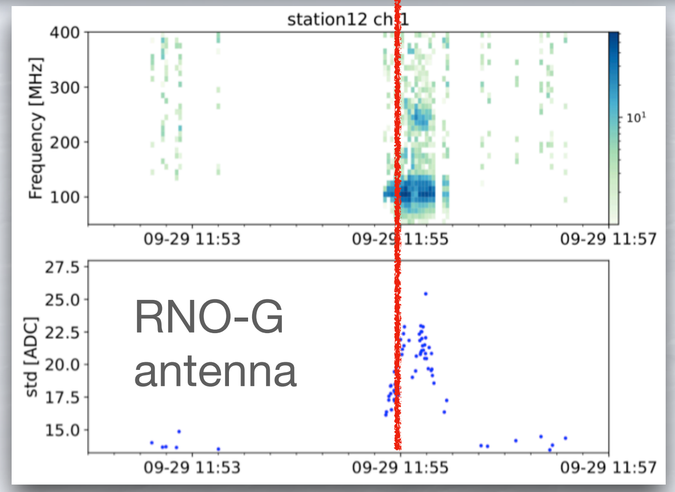
- Use natural glacier ice as target
- Radio waves are less attenuated in ice
  - A single radio station can monitor a cubic kilometer of ice
- Radio is a cost effective solution
  - In hardware & deployment
    (do not have to be deployed in
    3 km depth; 100 - 200 m is sufficient)

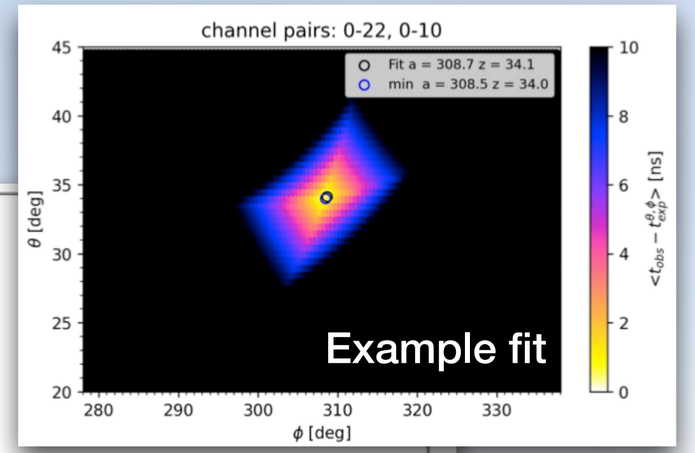


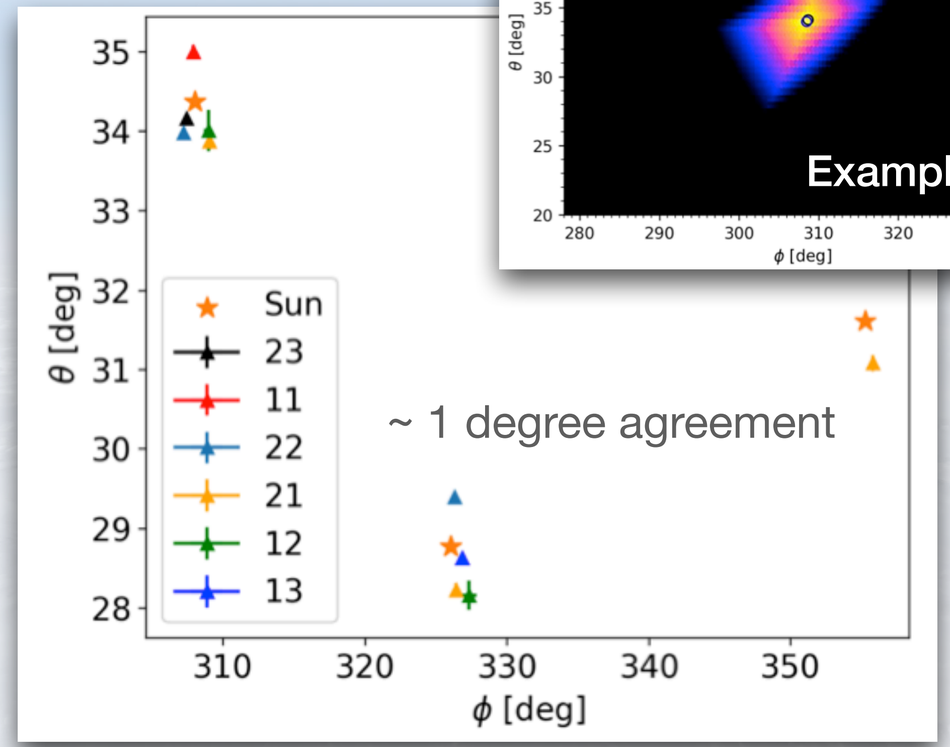
First look into the data: Solar flares

- For 3 solar flares, reconstruct position of Sun
- Allowed correction / calibration of station geometry





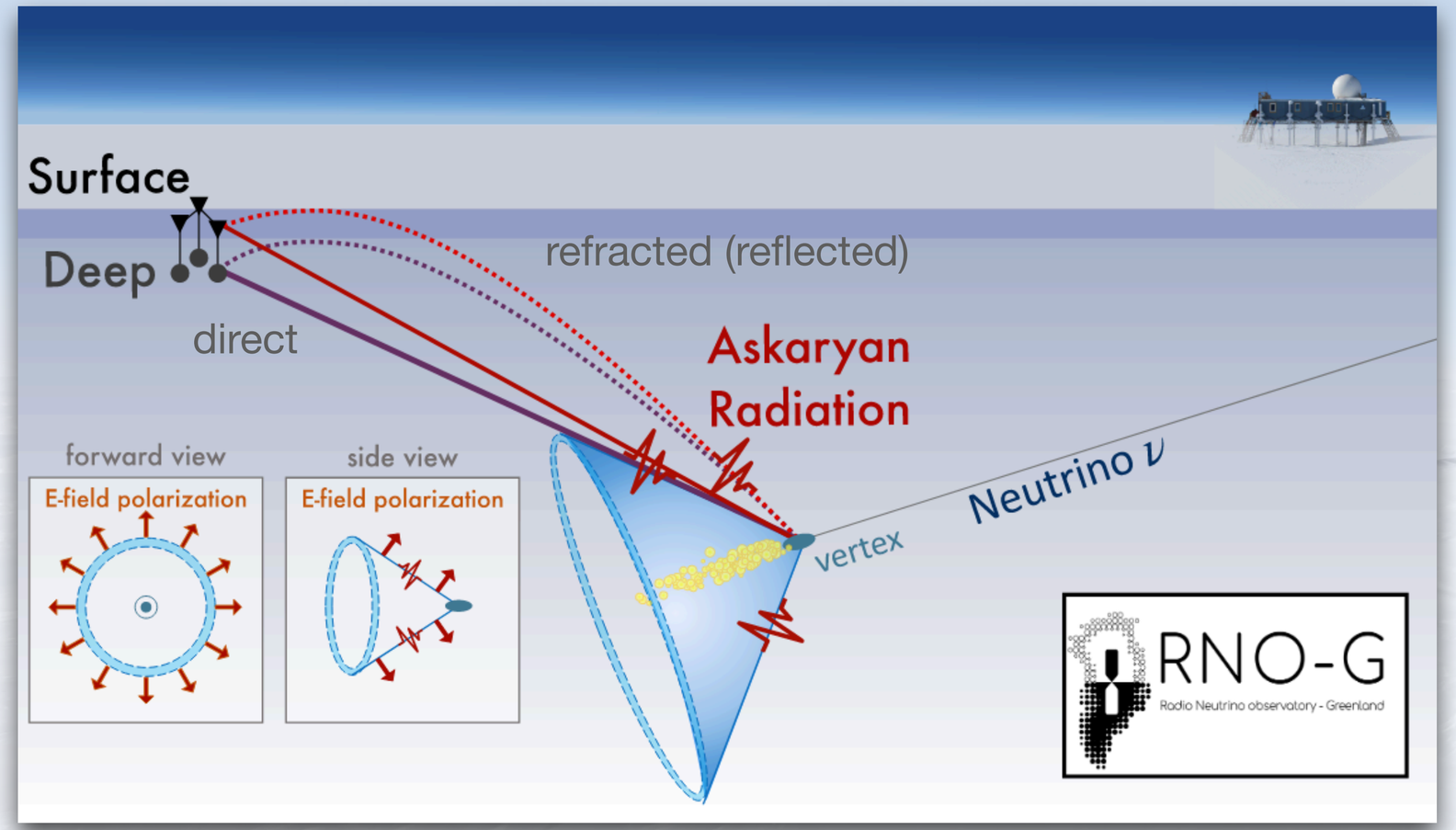




S. Hallmann for RNO-G, Pos (ICRC23) 1043

Radio detection of neutrinos

- Polarisation of electric field allows localisation on cone
- Several possible ray trajactories



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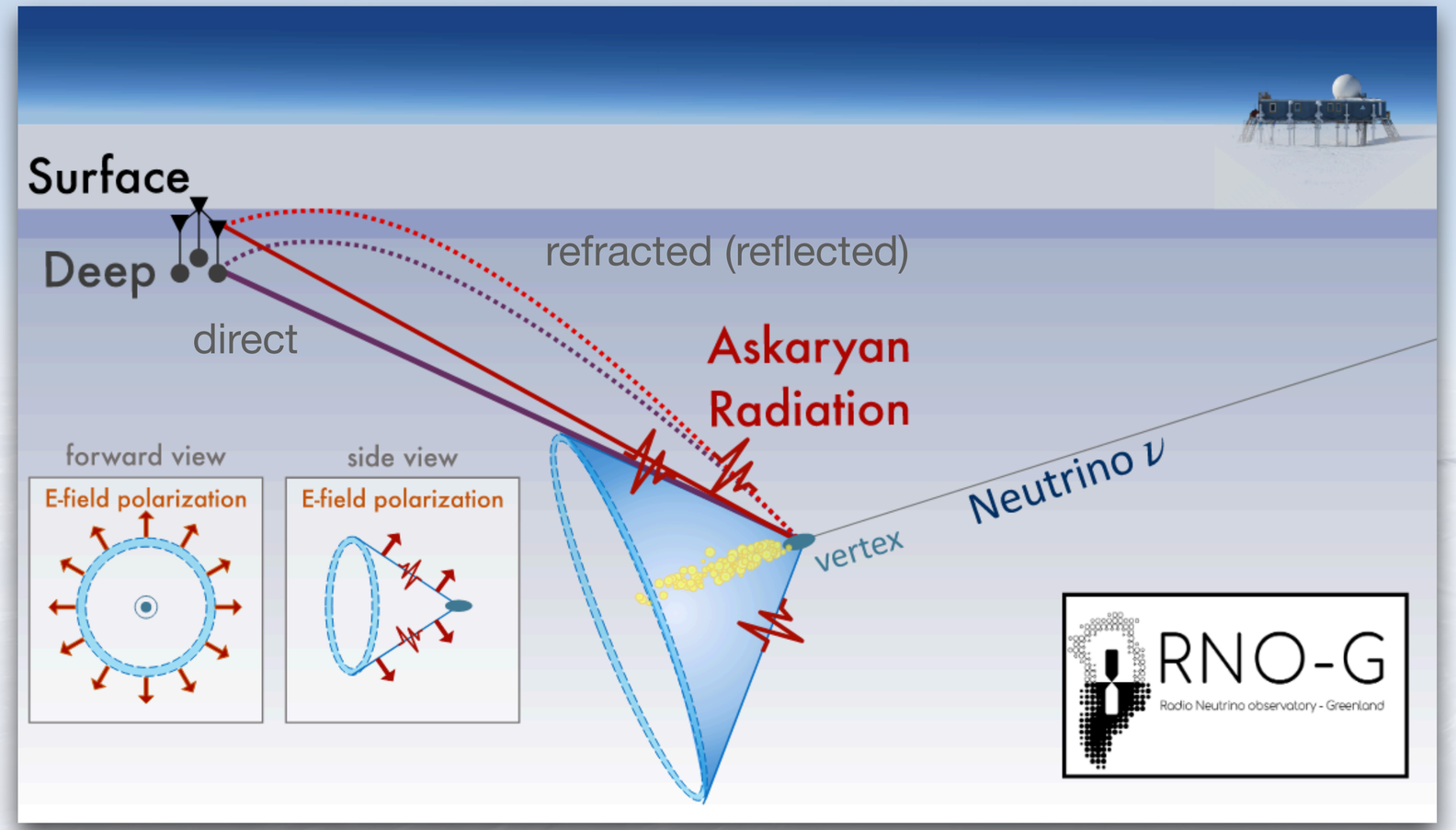
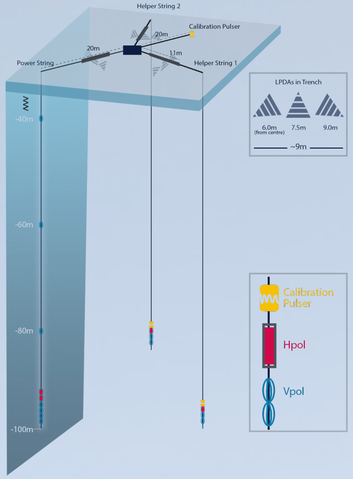


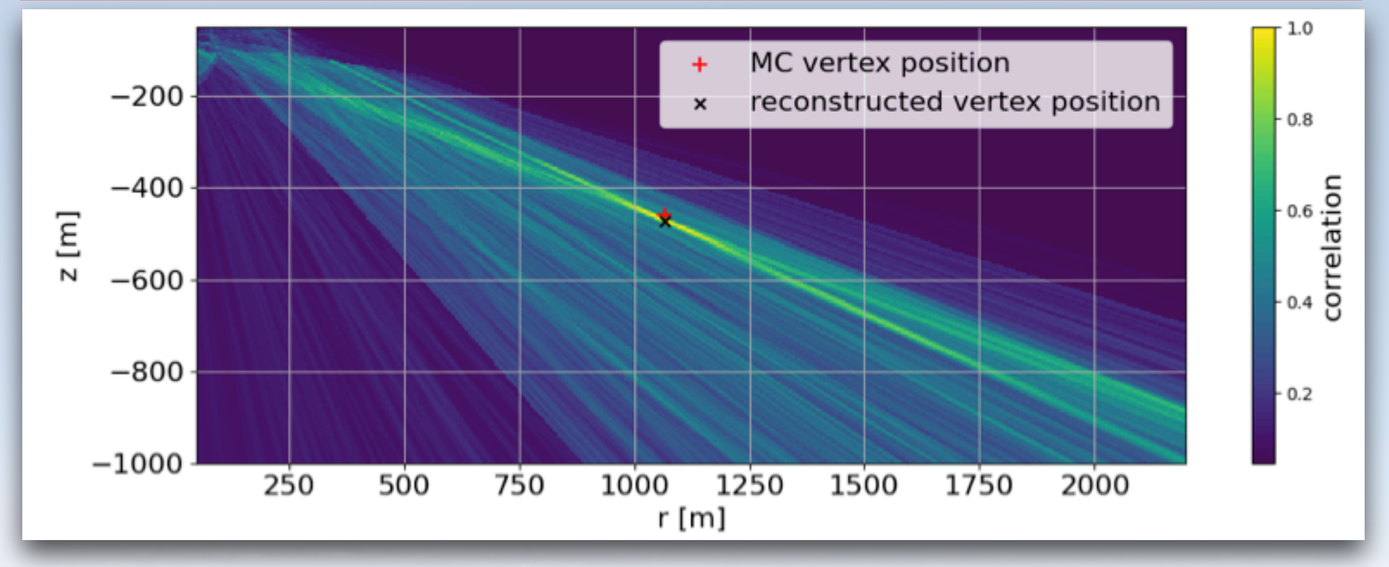
The radio emission …

- is produced by >PeV cascades
- illuminates a spherical (Cherenkov) cone
- gets bend in shallow ice
- propagates over km distances
- Signal features (frequency spectrum polarisation) allow to reconstruct neutrino properties

Arrival direction reconstruction



1. Reconstruct vertex position / signal arrival direction from triangulation



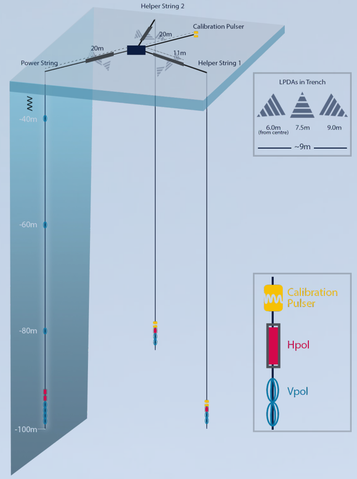
Using cross-correlation to determine signal (time) in each antenna.

Using forward folding technique to determine vertex position / signal arrival direction.

Requires signals in several strings

S. Bouma for IceCube-Gen2, Pos (ICRC23) 1045 I. Plaisier et.al., EPJC 83 (2023) 5

Arrival direction reconstruction



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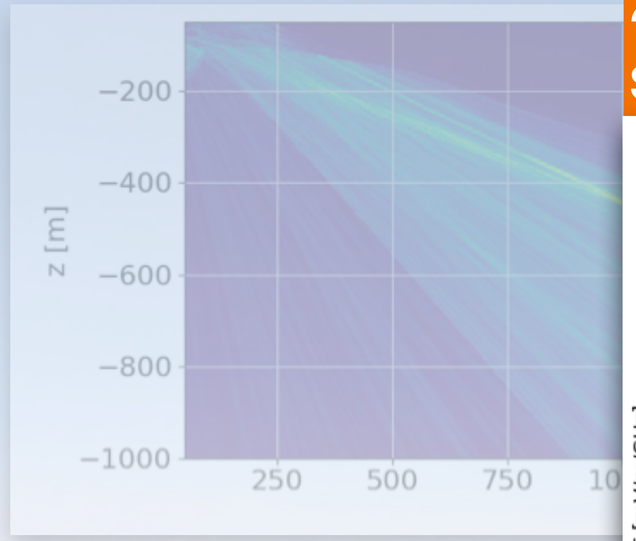

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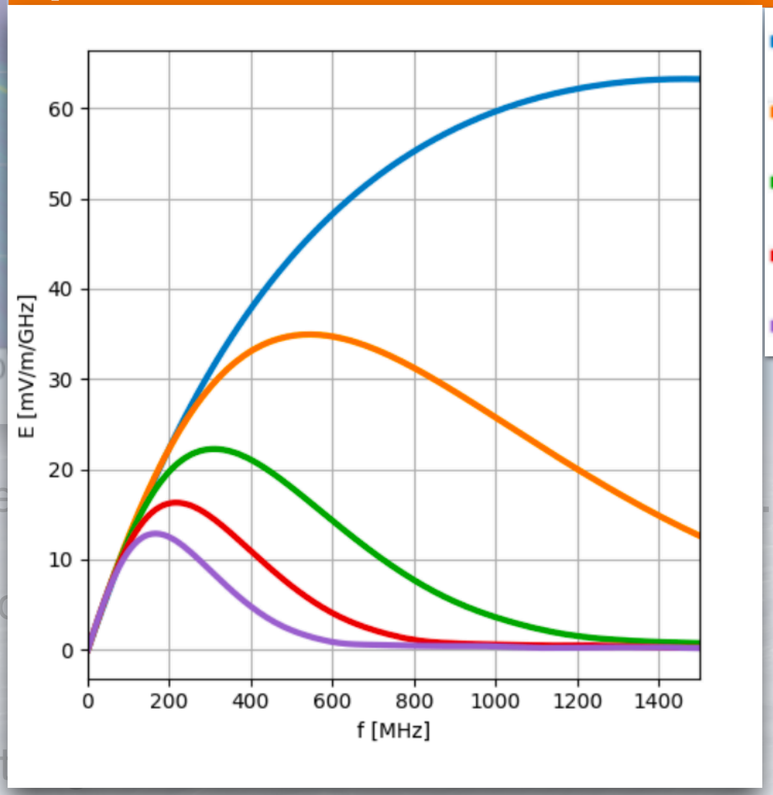
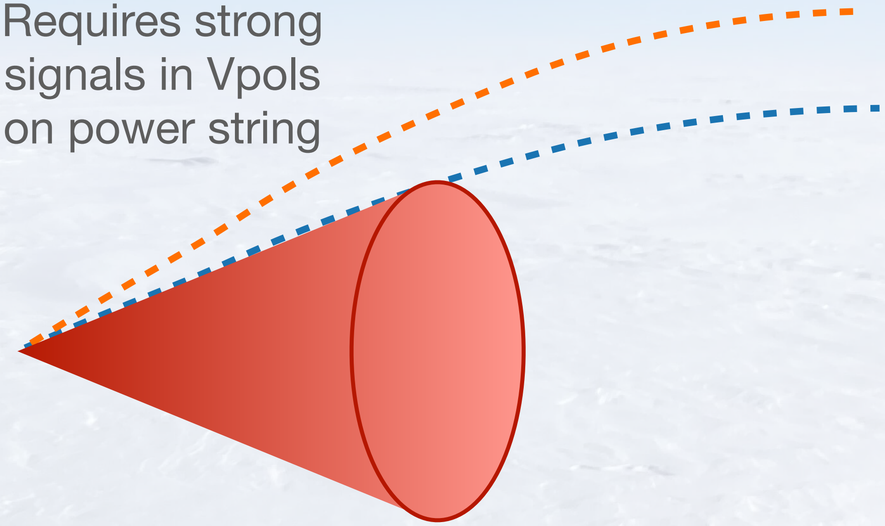
2. Reconstruct viewing angle from frequency spectrum



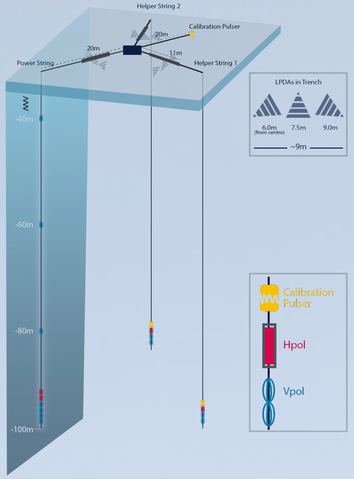
Requires strong signals in Vpols on power string



[S. Bouma for IceCube-Gen2, Pos (ICRC23) 1045]

[I. Plaisier et.al., EPJC 83 (2023) 5]

Arrival direction reconstruction



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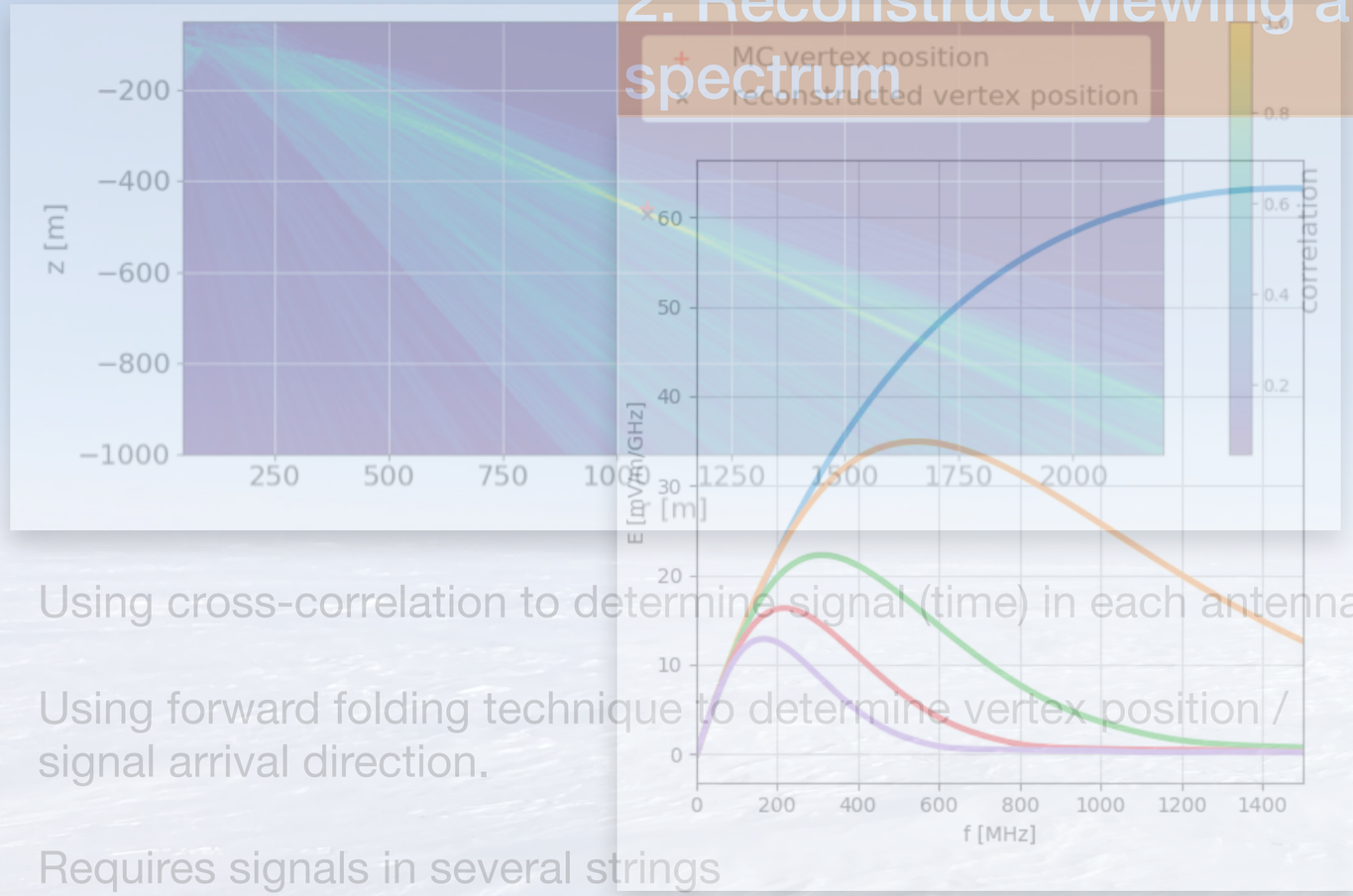

Using cross-correlation to determine signal (time) in each antenna.

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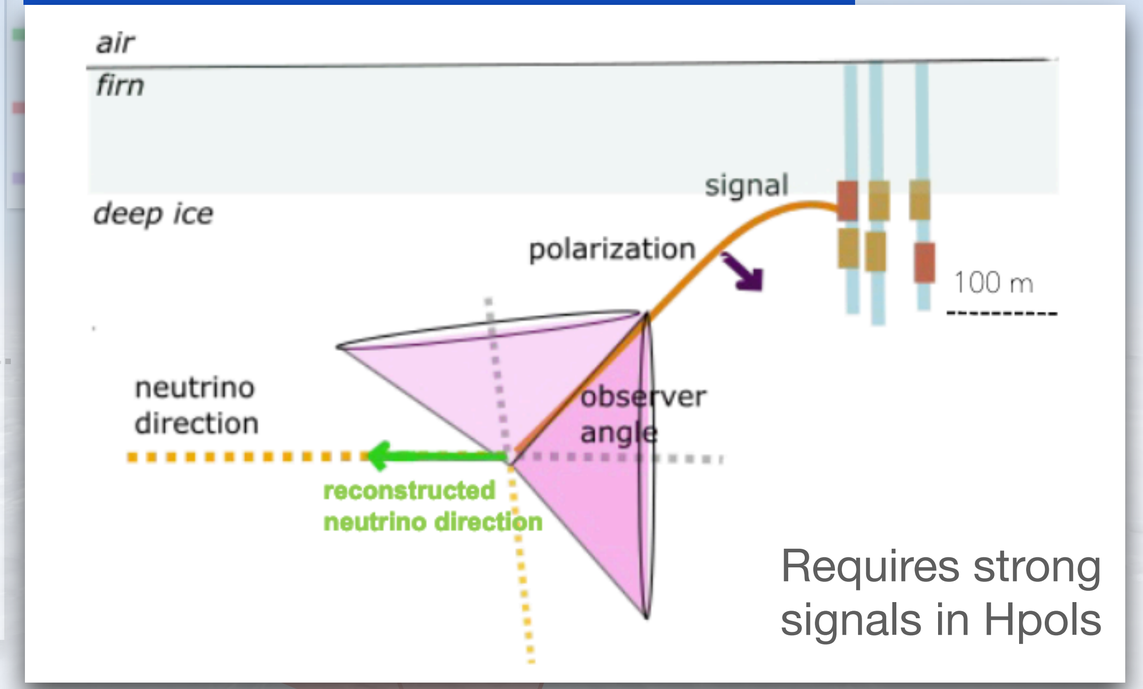
Requires signals in several strings

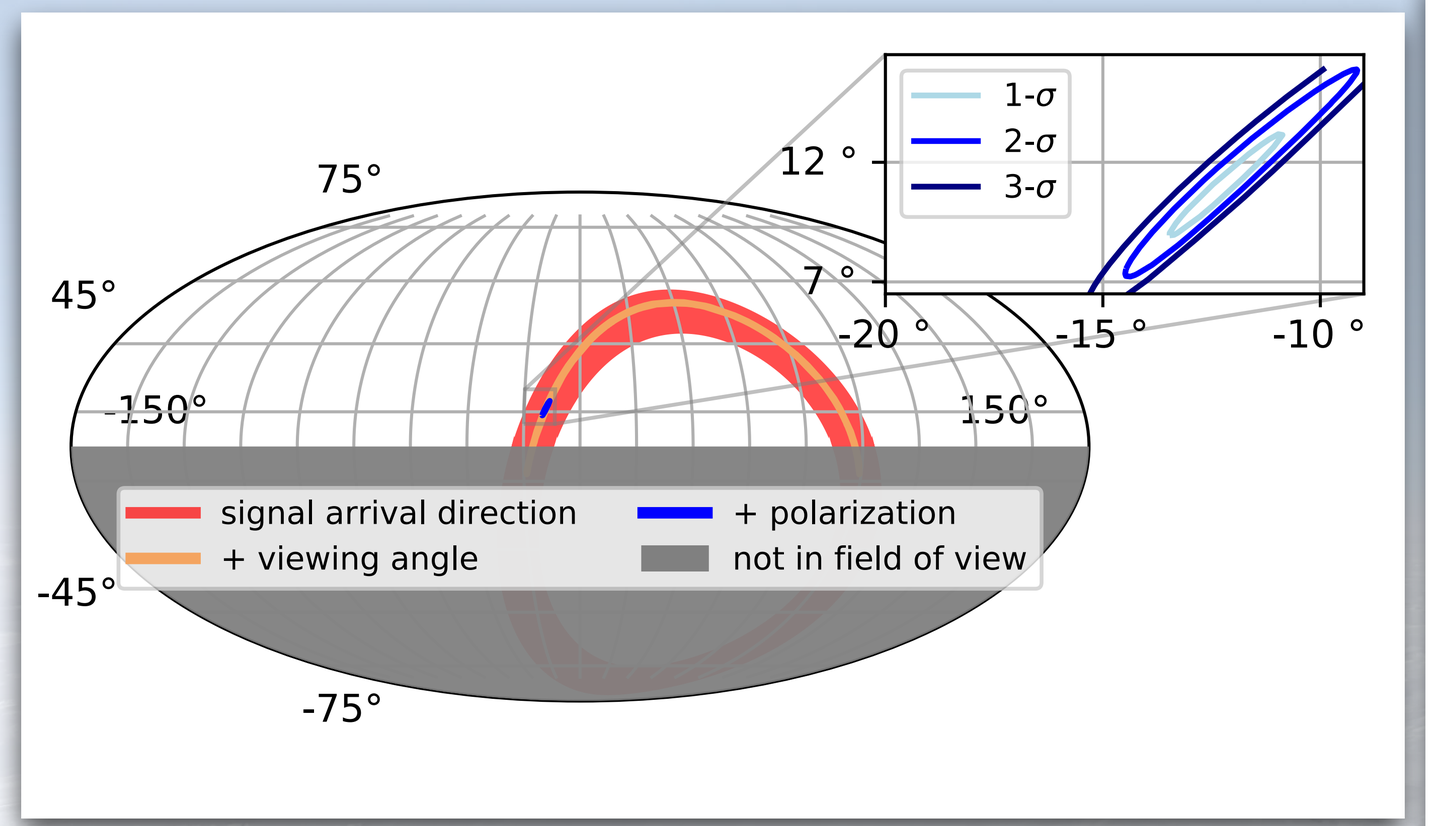
$\theta - \theta_{Cherenkov} = 0^\circ$

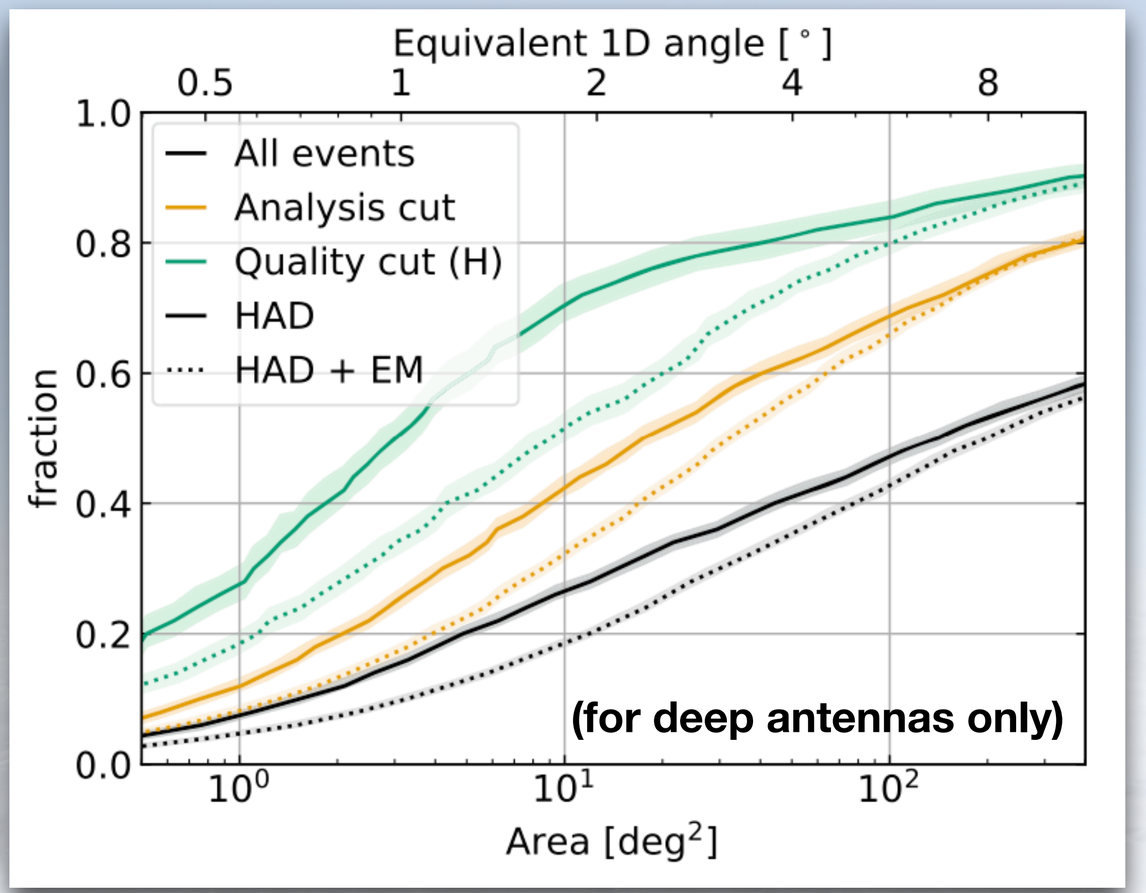
3. Reconstruct polarisation



S. Bouma for IceCube-Gen2, Pos (ICRC23) 1045 I. Plaisier et.al., EPJC 83 (2023) 5

Arrival direction reconstruction





S. Bouma for IceCube-Gen2, Pos (ICRC23) 1045 I. Plaisier et.al., EPJC 83 (2023) 5

Energy reconstruction

RNO-G, EPJC 82, 147 (2022) RNO-G, JINST 16 (2021) 03

Observed Field

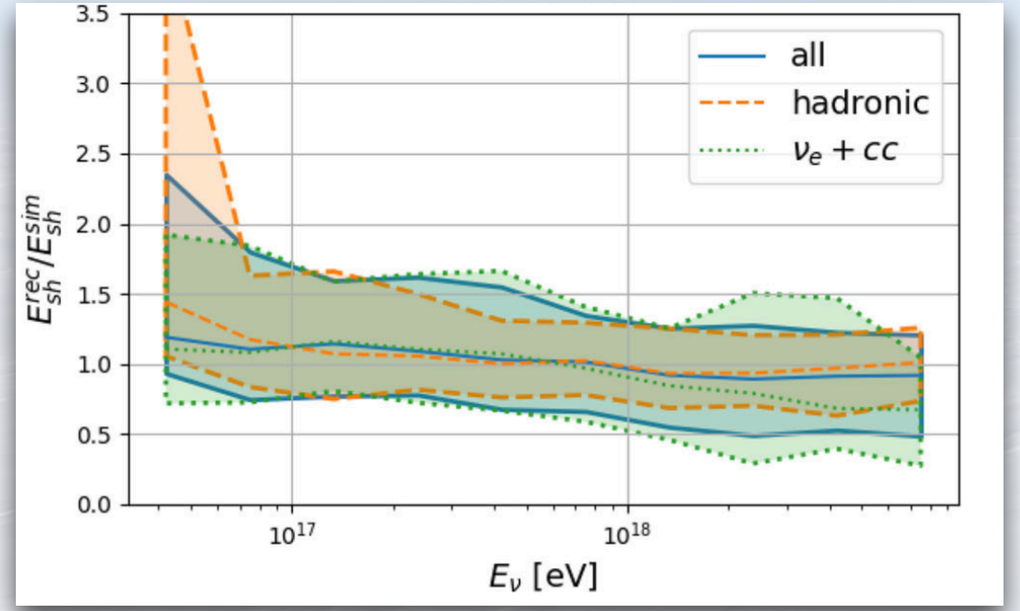
Viewing angle

Vertex Distance

Polarization

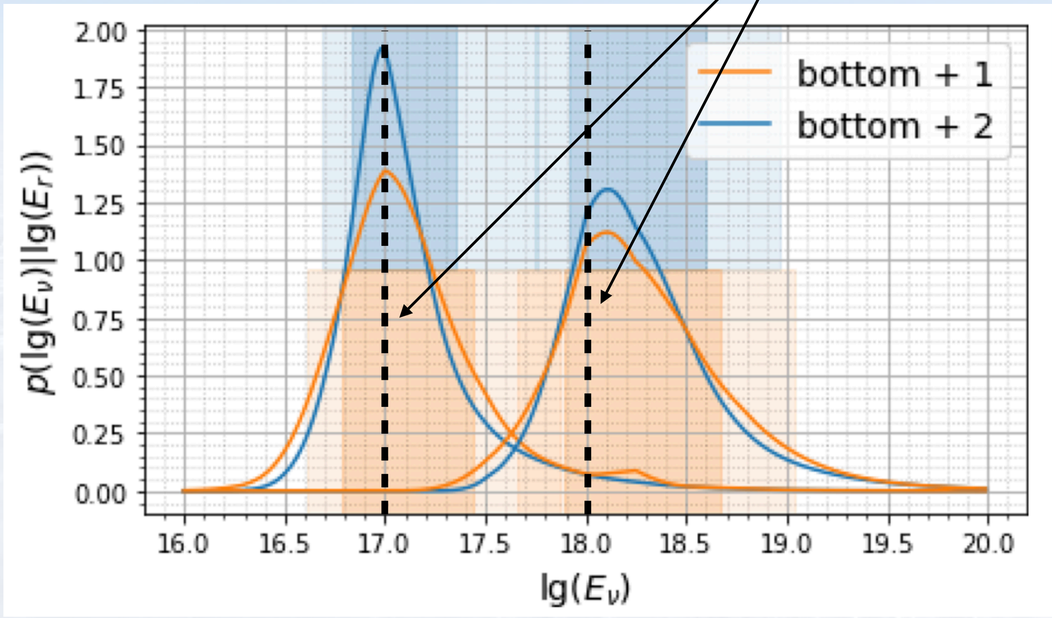
$$\vec{\mathcal{E}}(f) \propto (1-y)E_\nu \exp\left[-\frac{1}{2}\left(\frac{\theta-\theta_c}{\sigma(E_{sh},f)}\right)^2\right] \frac{1}{R}\exp\left(\frac{-R}{L(f)}\right) \vec{\ell}\times(\vec{v}_\nu\times\vec{\ell})$$

Shower energy



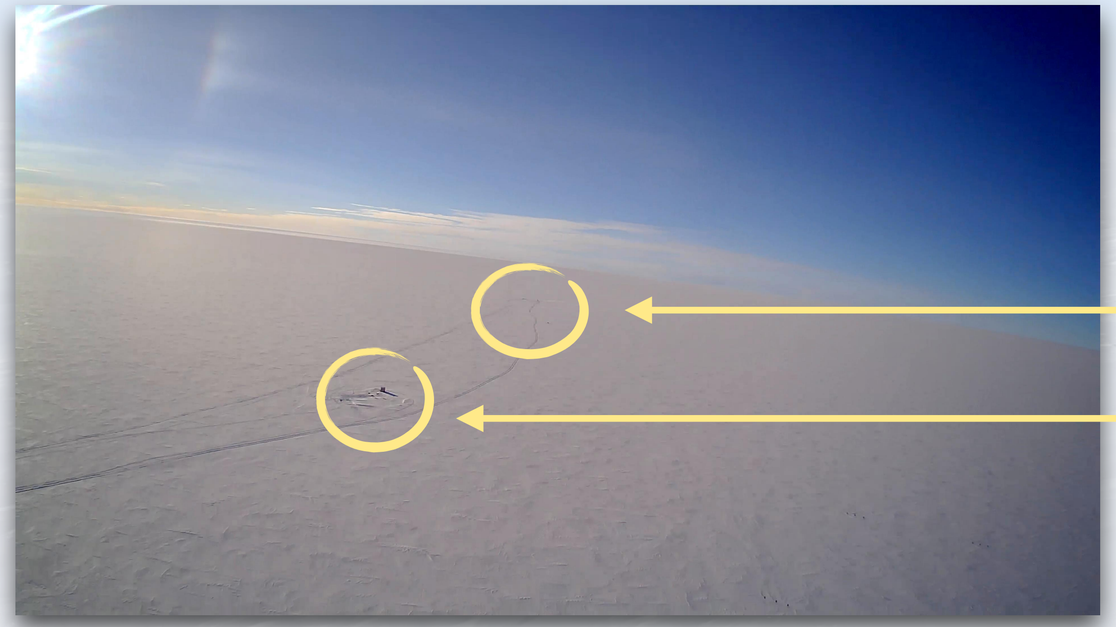
Neutrino energy

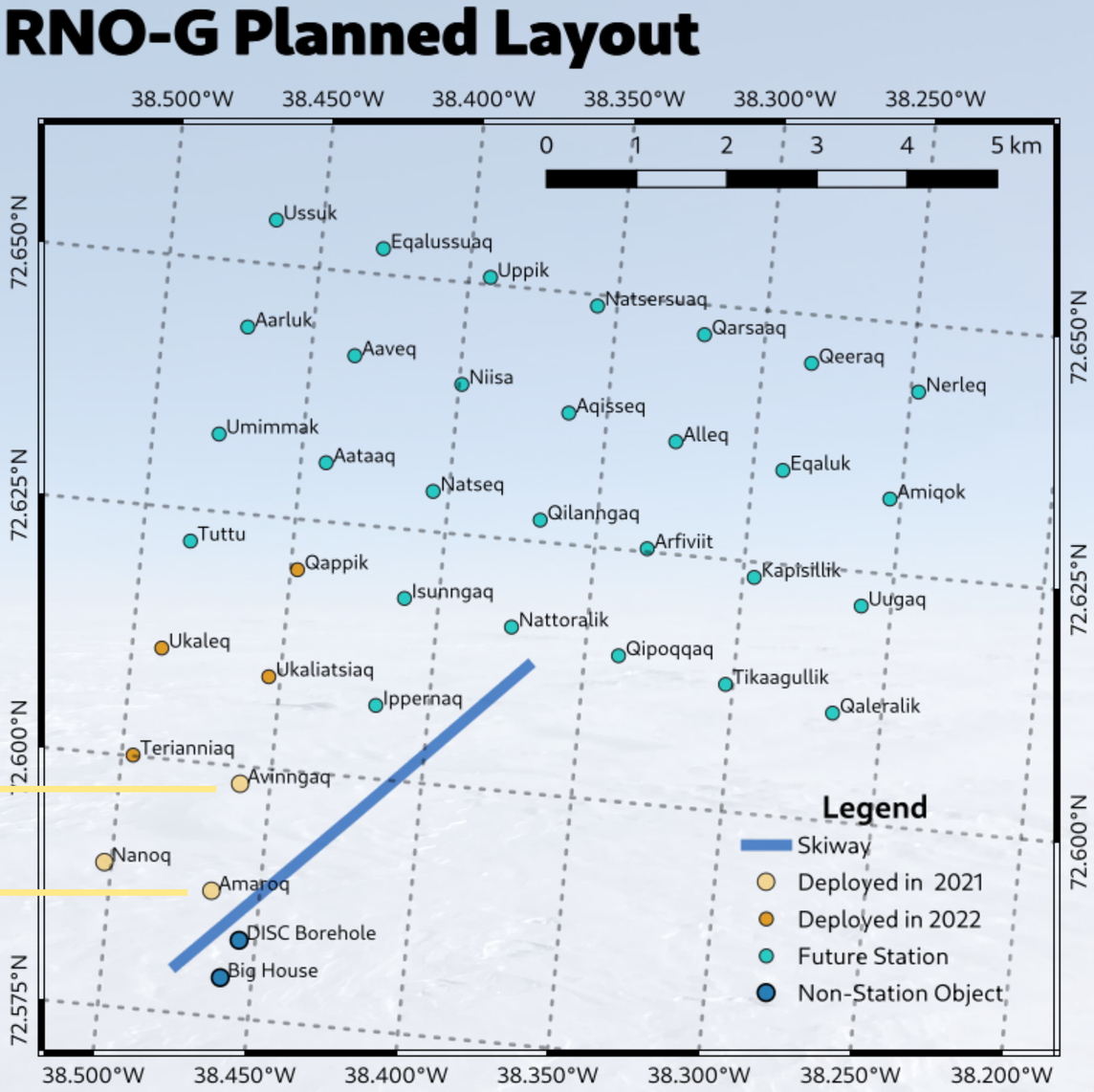
True energy



Radio Neutrino Observatory - Greenland

- 35 stations on 1.25km grid
  - 7 already deployed & taking data
  - 3 - 4 more deployment seasons
- Stations are solar powered & communicate wireless

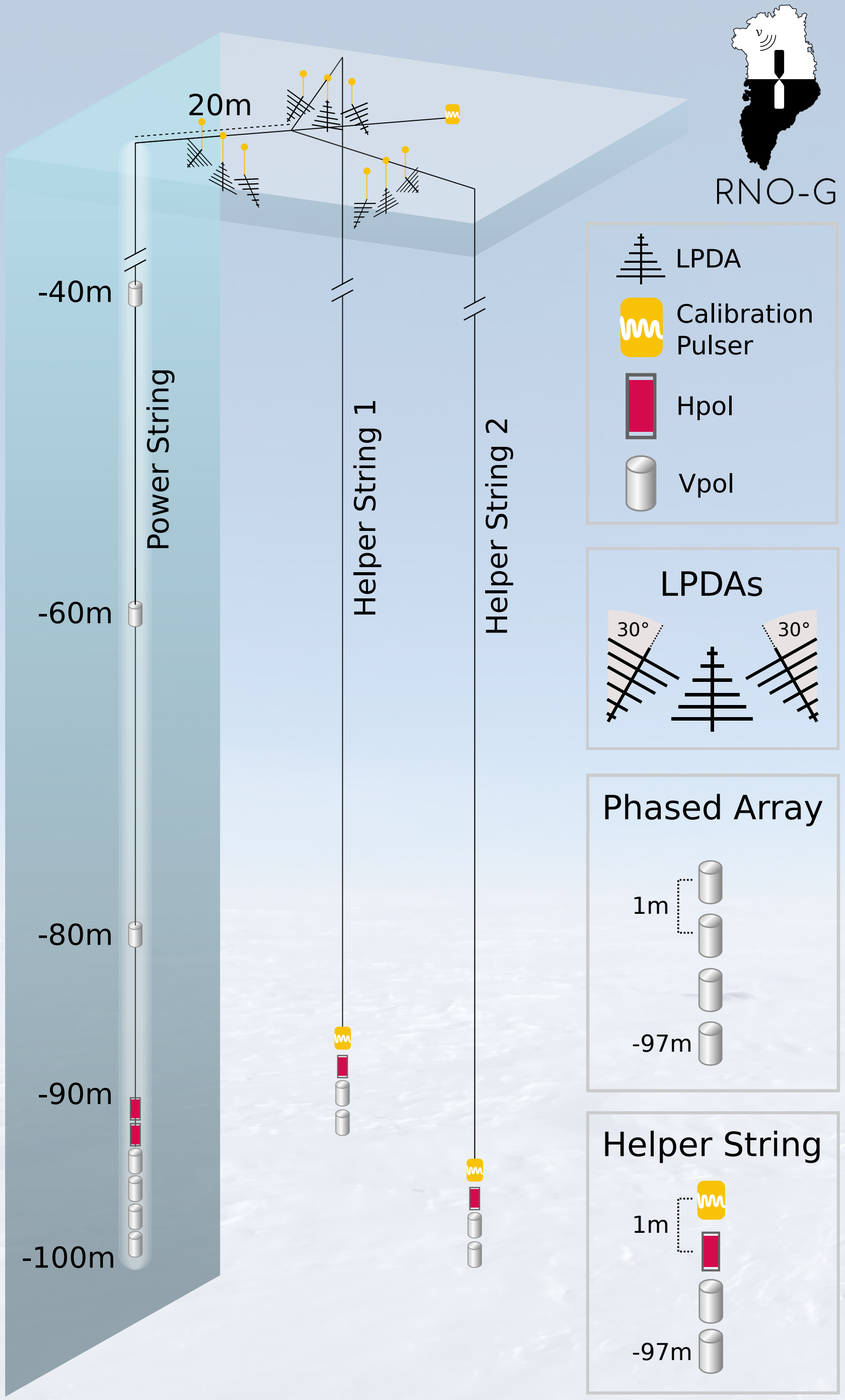




Station design

A hybrid concept

- 24 antennas
  - 3 types; 80 - 650 MHz
- 3 calibration pulsar
- Informed by pilot experiments (ARA & ARIANNA)
- Will inform IceCube-Gen2 radio array design



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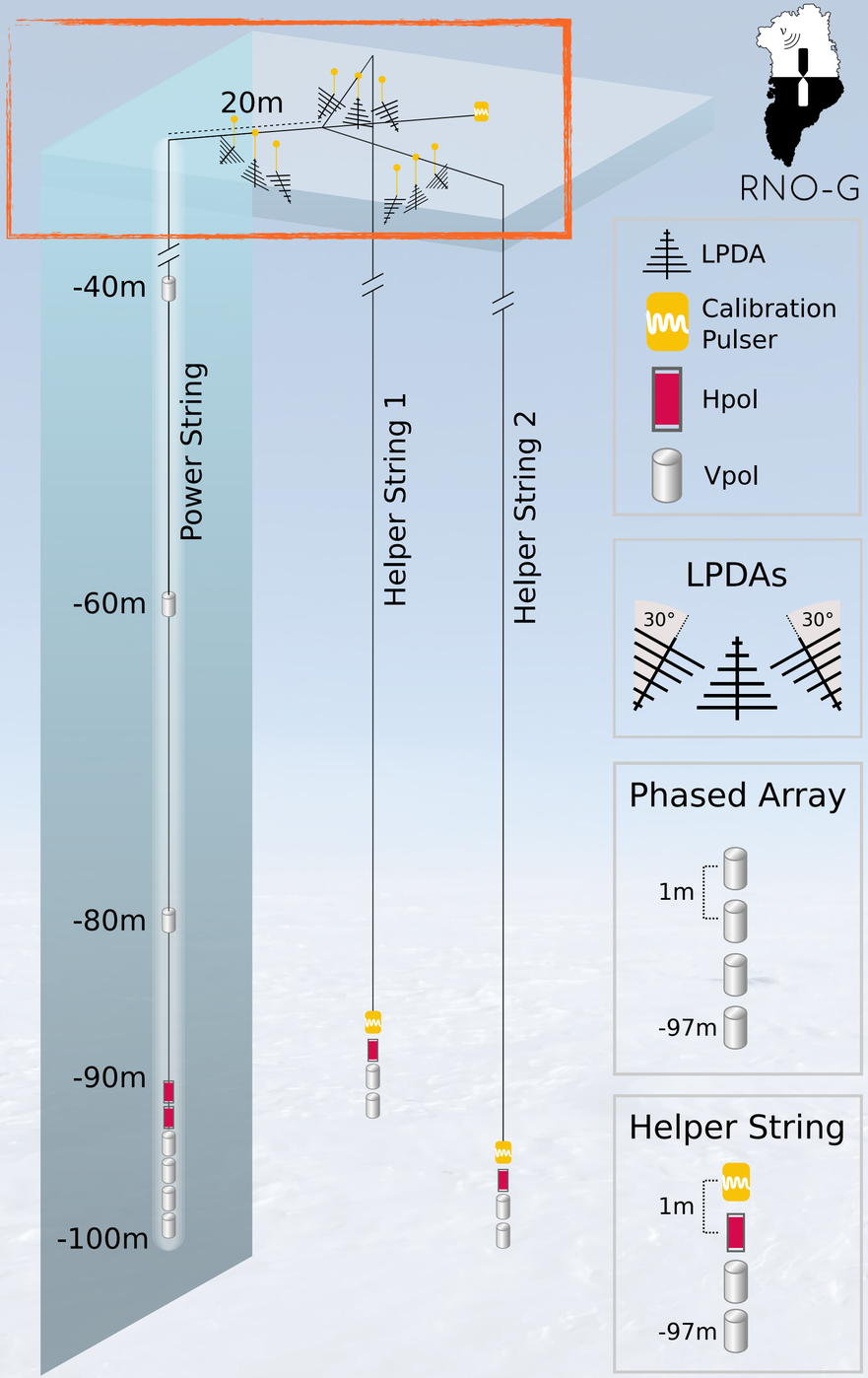

Shallow component

- Upward- & downward-facing LPDA antennas
- CR detection + veto
- Accurate polarisation reconstruction
- Multiple coincidence threshold trigger

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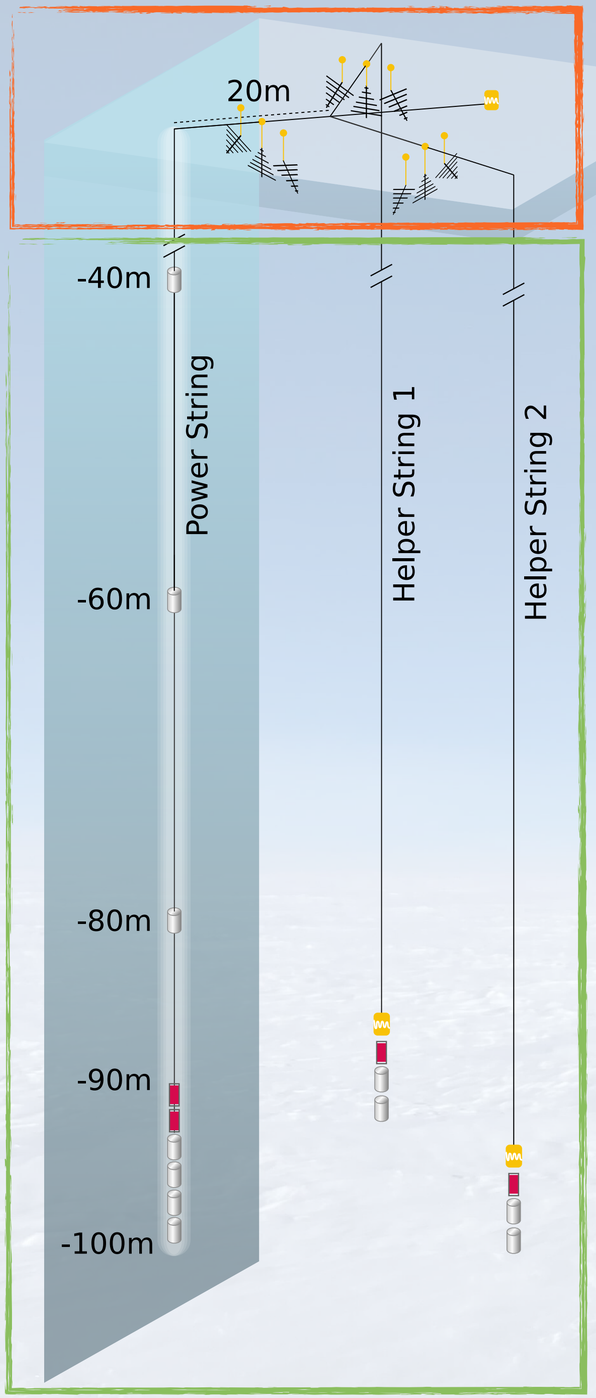

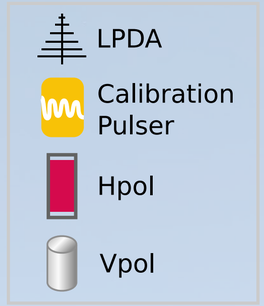

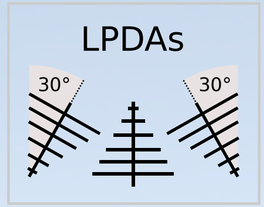

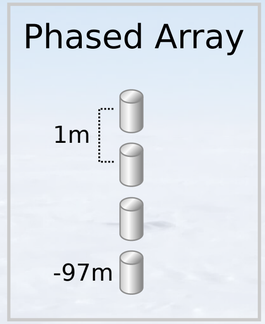

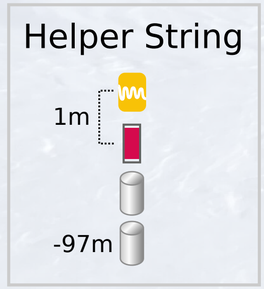

Shallow component

- Upward- & downward-facing LPDA antennas
- CR detection + veto
- Accurate polarisation reconstruction
- Multiple coincidence threshold trigger

Deep component

- 100m deep
- “Overlook” larger volume
- Low threshold trigger

Station design

A hybrid concept

- 24 antennas
  - 3 types; 80 - 650 MHz
- 3 calibration pulsar
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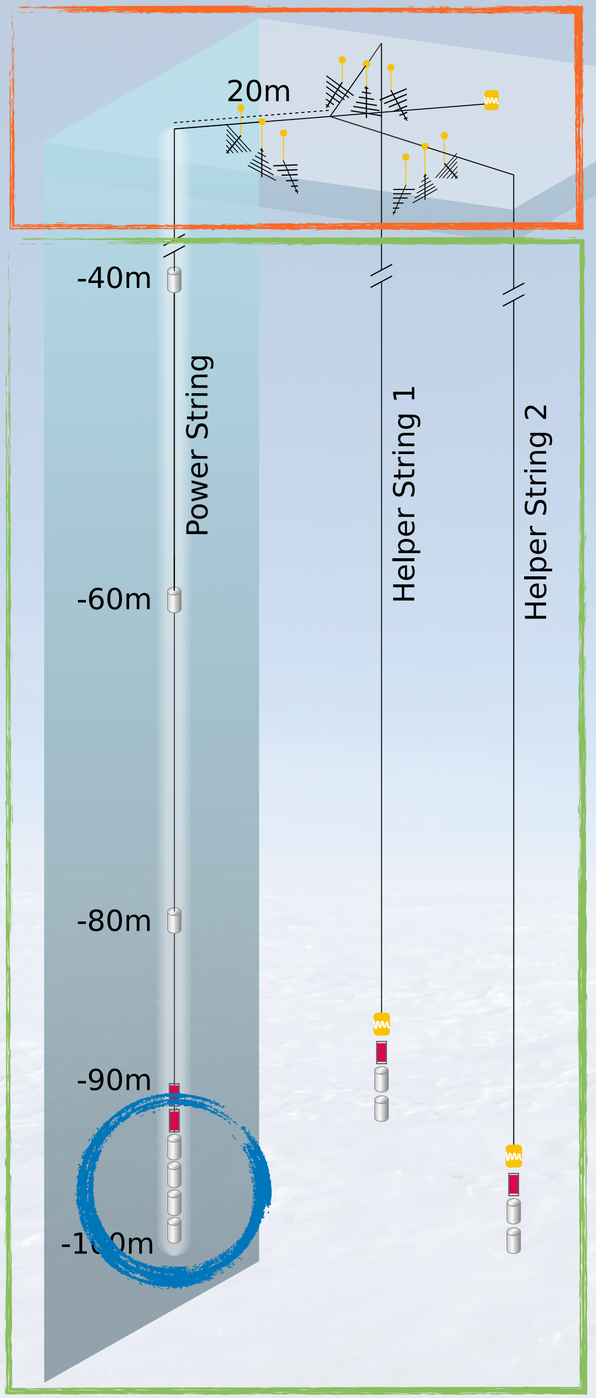
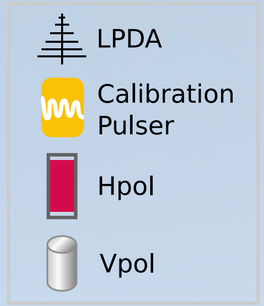
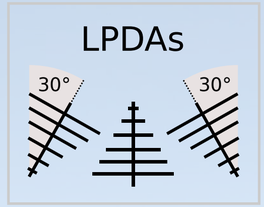
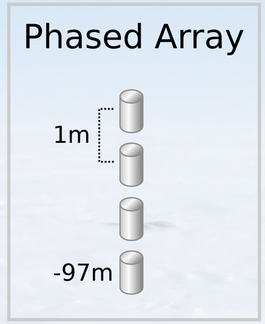
Phased array

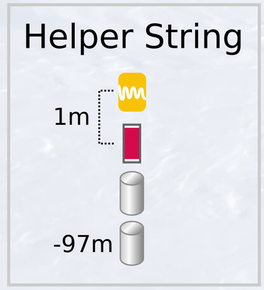
- Signal of 4 Vpols combined by phasing into 8 beams in real time











Shallow component

- Upward- & downward-facing LPDA antennas
- CR detection + veto
- Accurate polarisation reconstruction
- Multiple coincidence threshold trigger

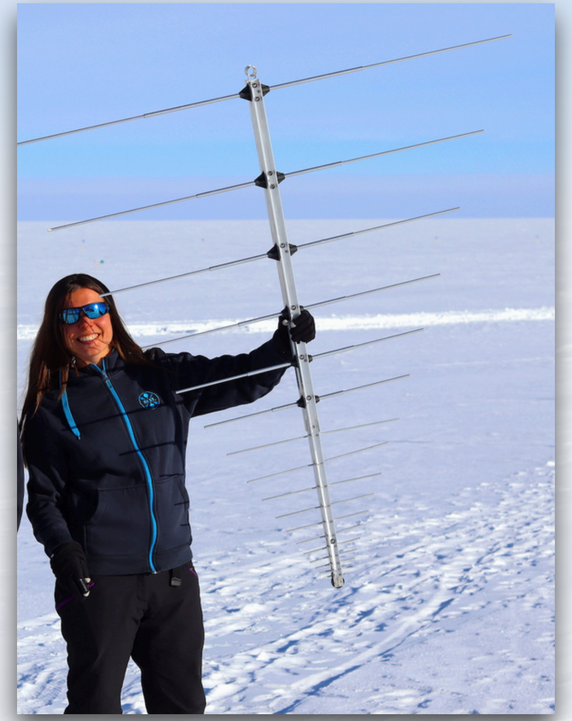
Deep component

- 100m deep
- “Overlook” larger volume
- Low threshold trigger

Antenna sensitivity

- LPDA is more sensitive but can not be deployed in borehole
  - 2 orthogonal LPDAs → Polarisation

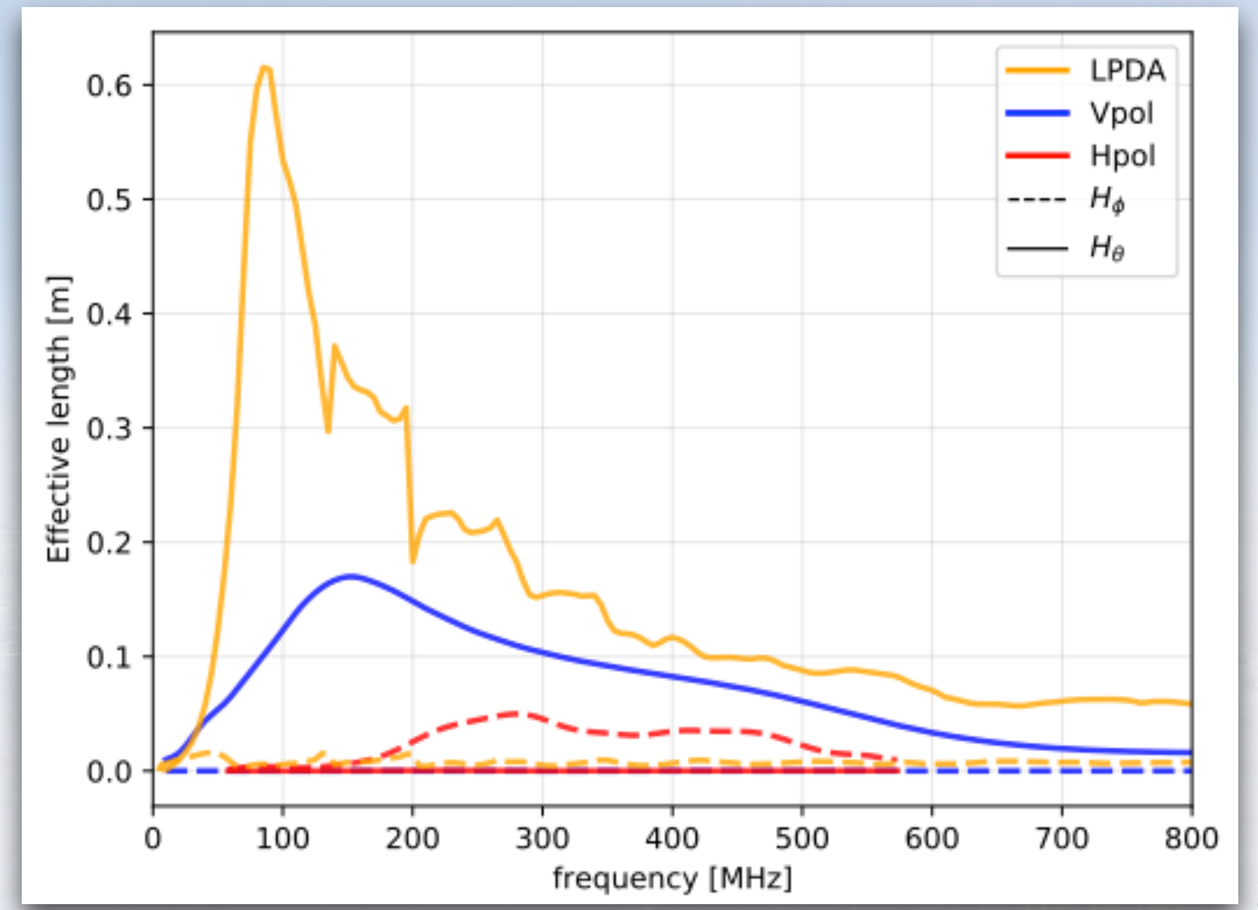
LPDA



Hpol

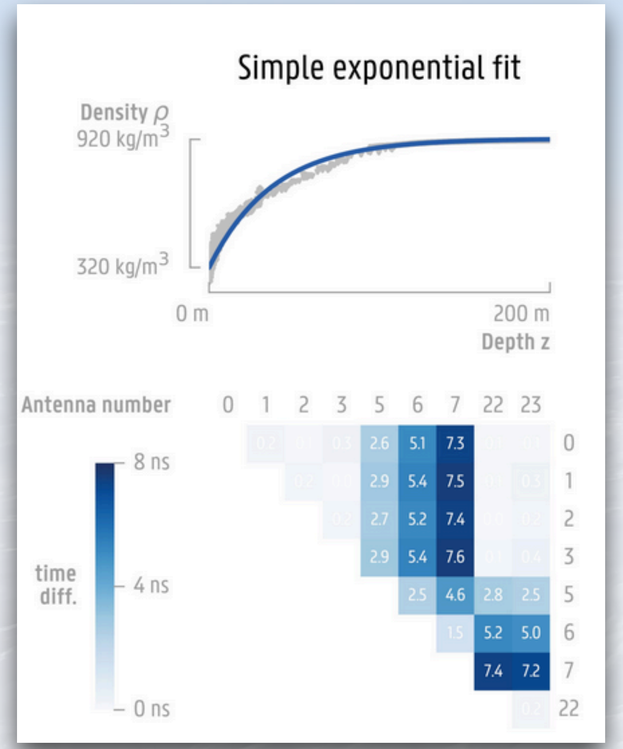
Vpol

- Combination of Vpol and Hpol gives polarisation
  - Hpols is less sensitive because of narrow diameter of borehole



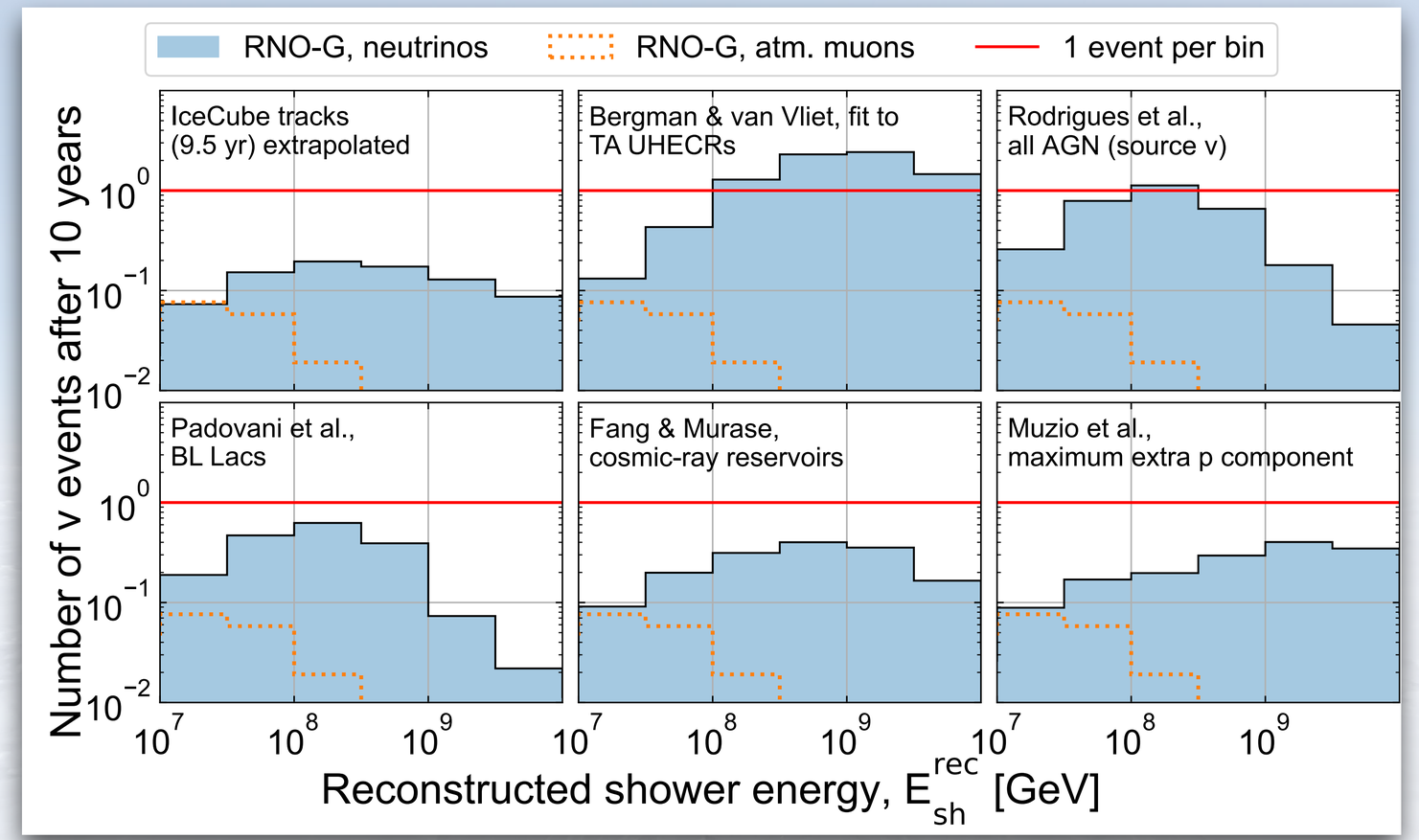
Calibration

- The ice is part of our detector
  - Refractive index profile of crucial importance
  - ➡ See Talk by Bob Oeyen this afternoon



Expected number of neutrinos

- Several models predict at least one neutrino when integrating over the energy

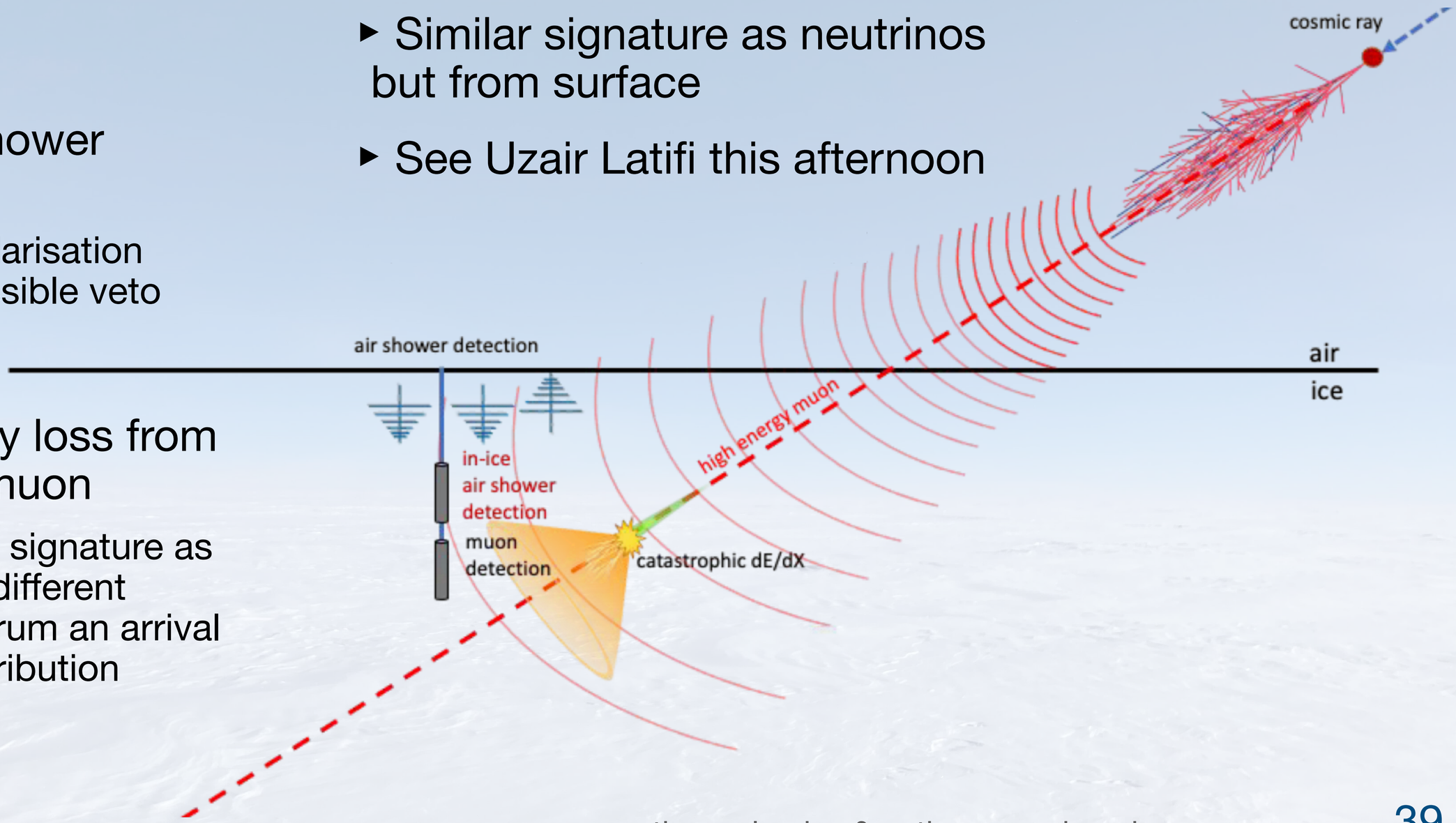


Background

1. Direct air shower emission
   - Different polarisation pattern, possible veto

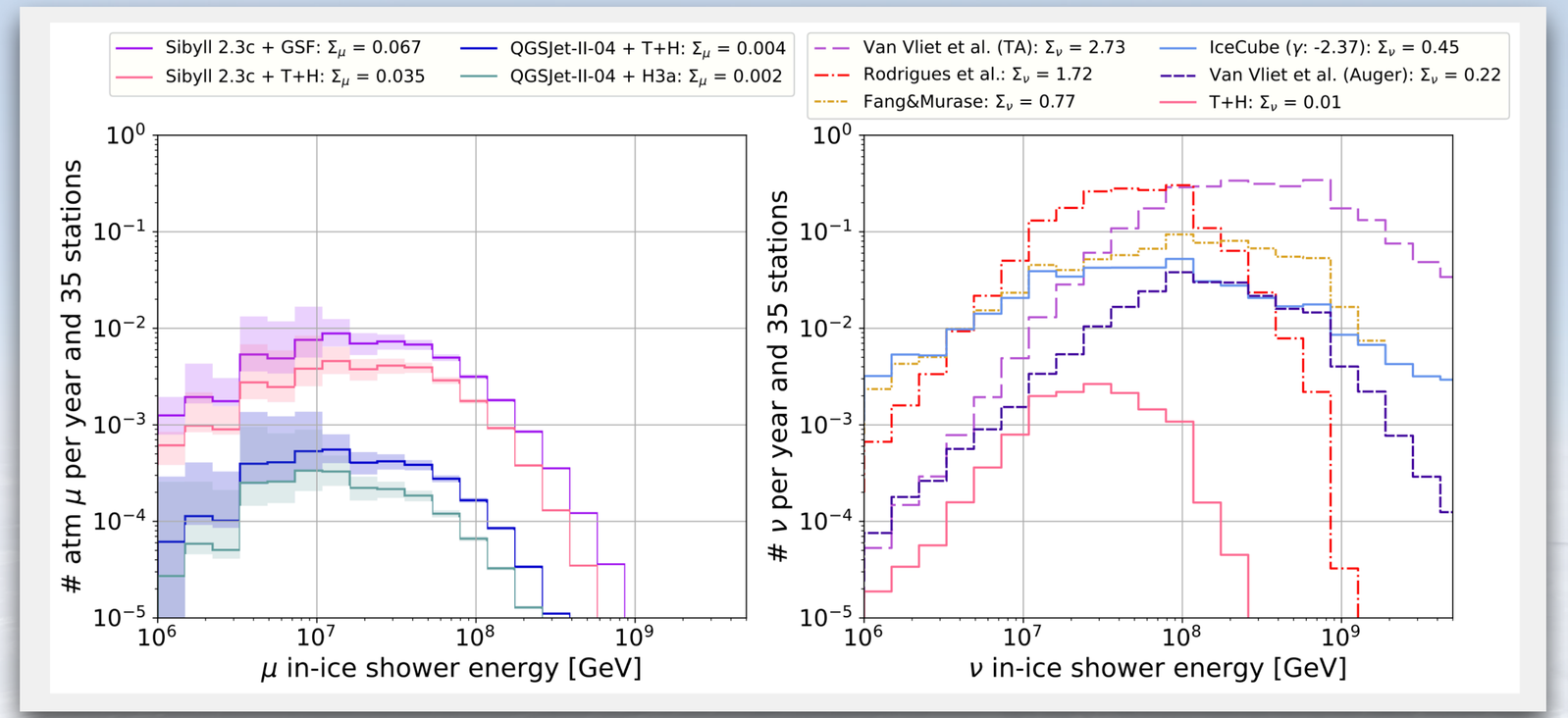
2. Huge energy loss from high energy muon
   - Same signal signature as neutrino but different energy spectrum an arrival direction distribution

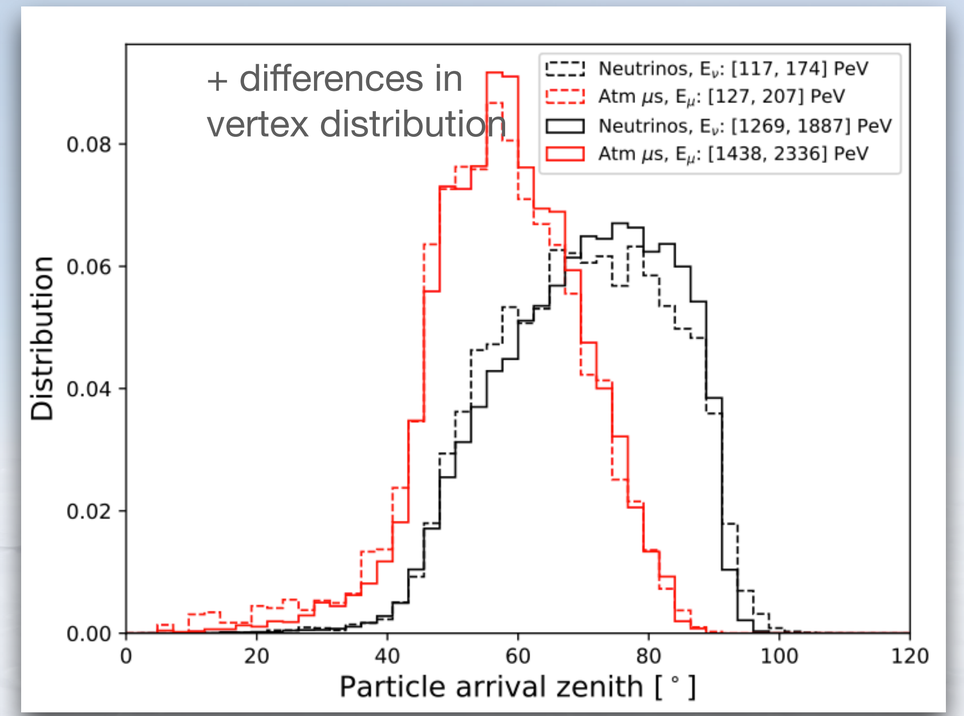
3. In-ice emission if air shower particles reach ice
   - Similar signature as neutrinos but from surface
   - See Uzair Latifi this afternoon



+ thermal noise & anthropogenic noise

Background



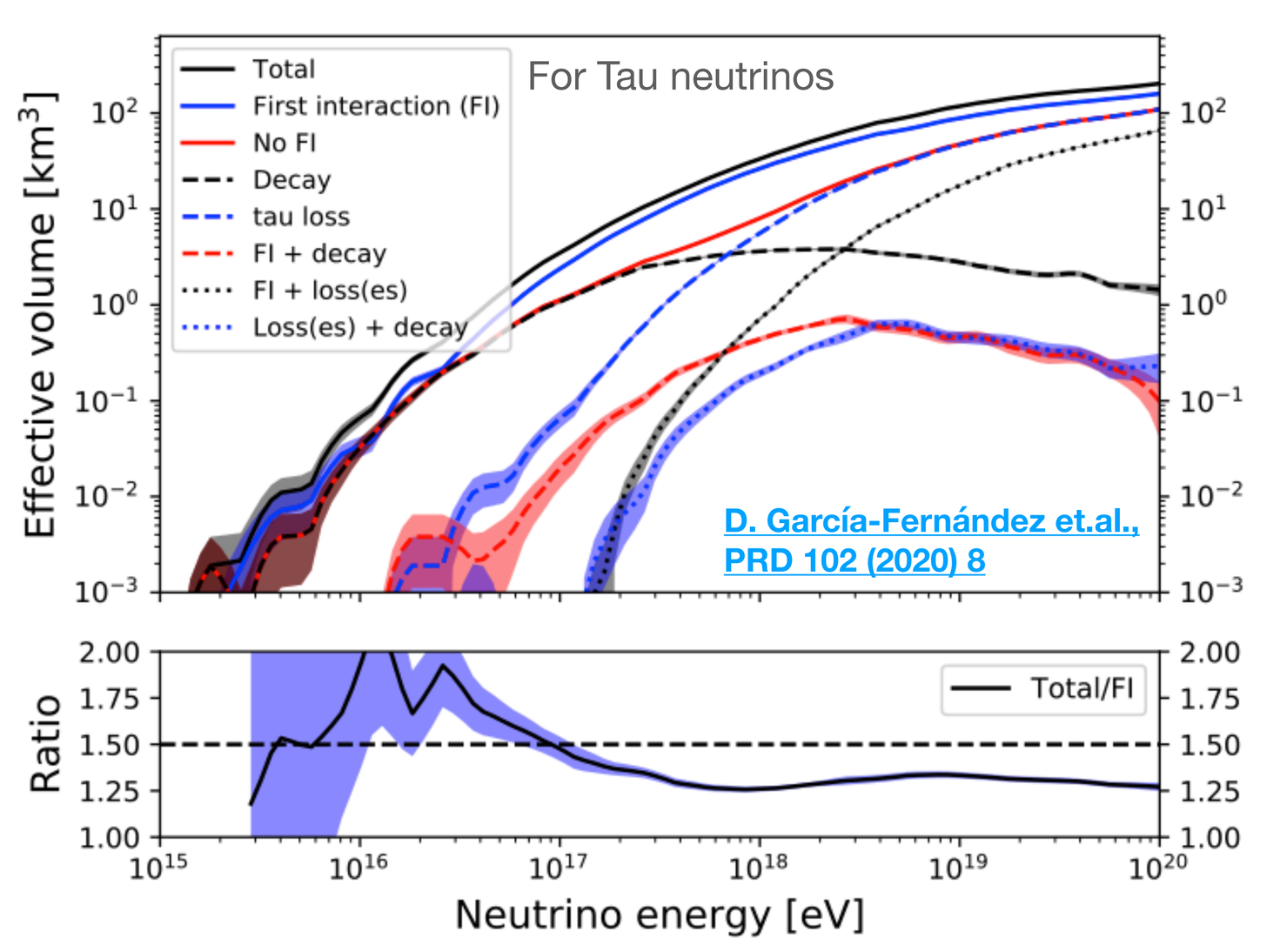


[L. Pyras et al. PoS (ICRC2023) 1076](#) [+ arxiv](#)

Ice Properties

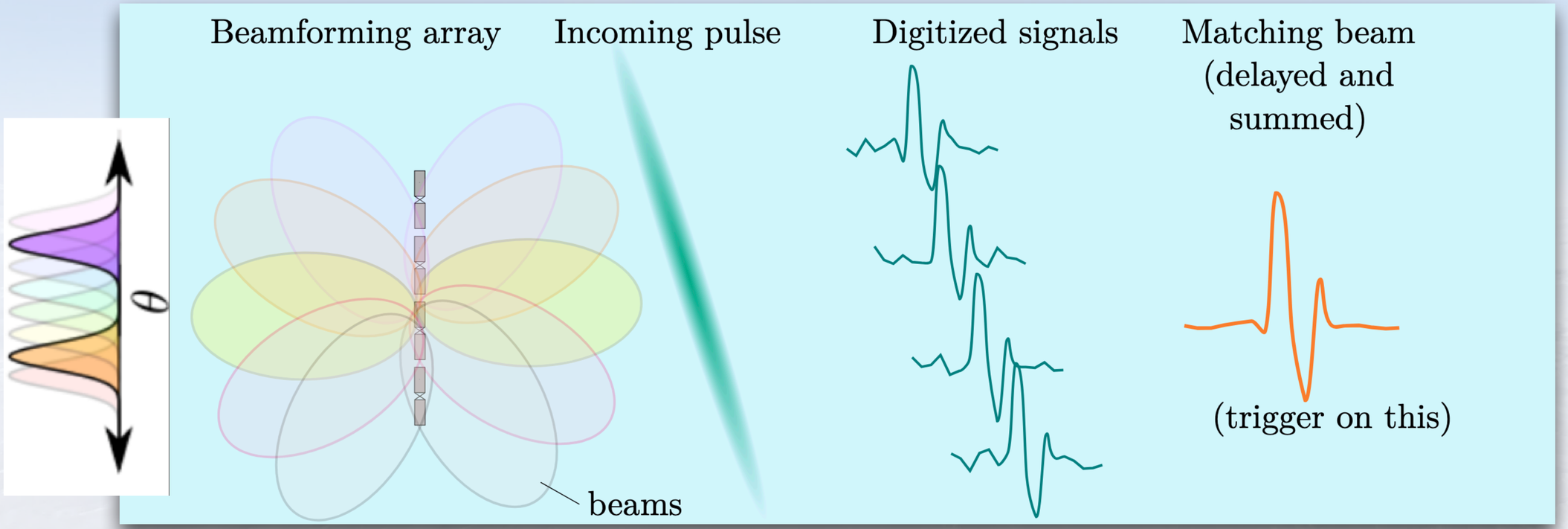
- Part of the detector -> needs to be calibrated

Signals from secondary leptons

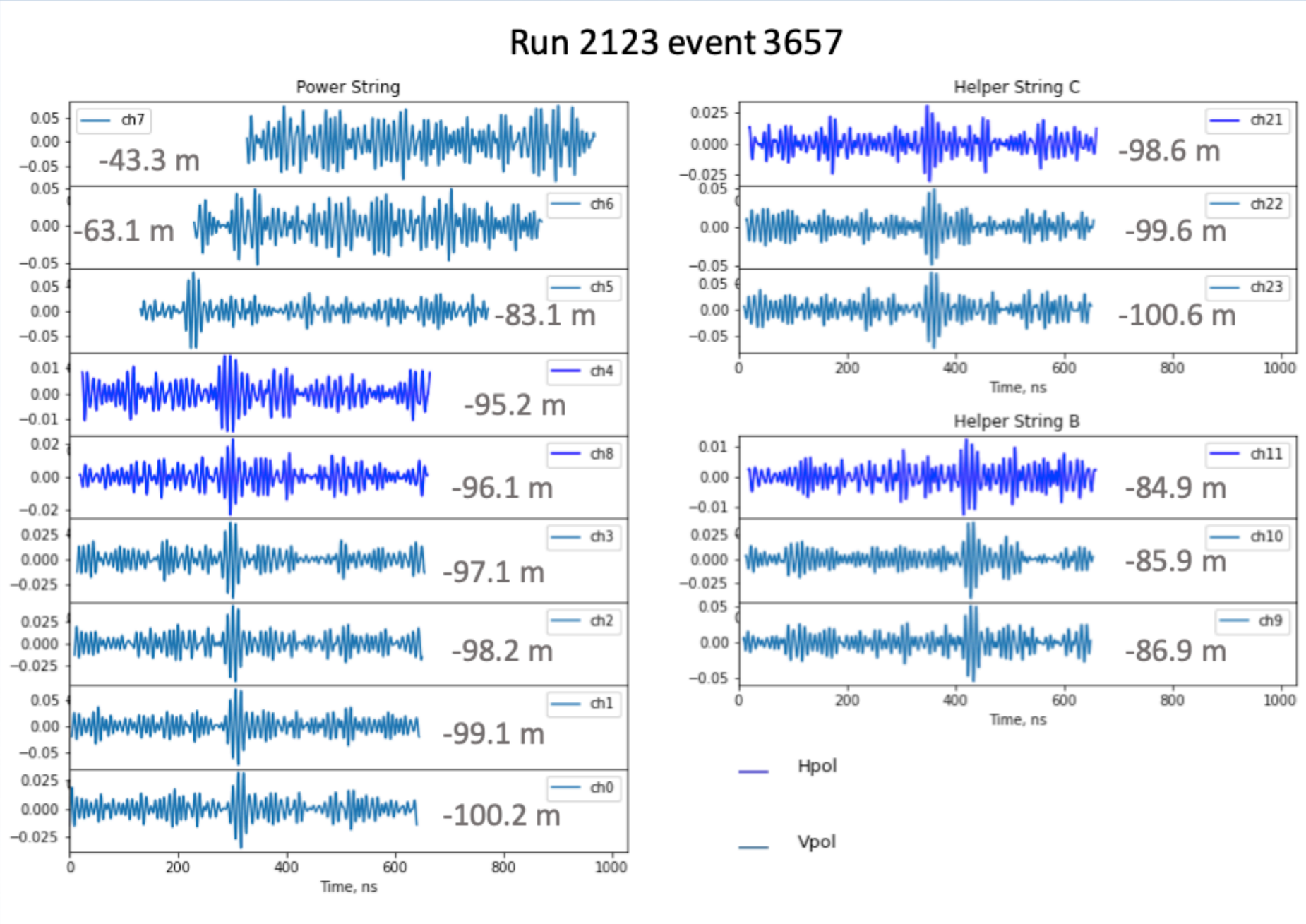


Phased array

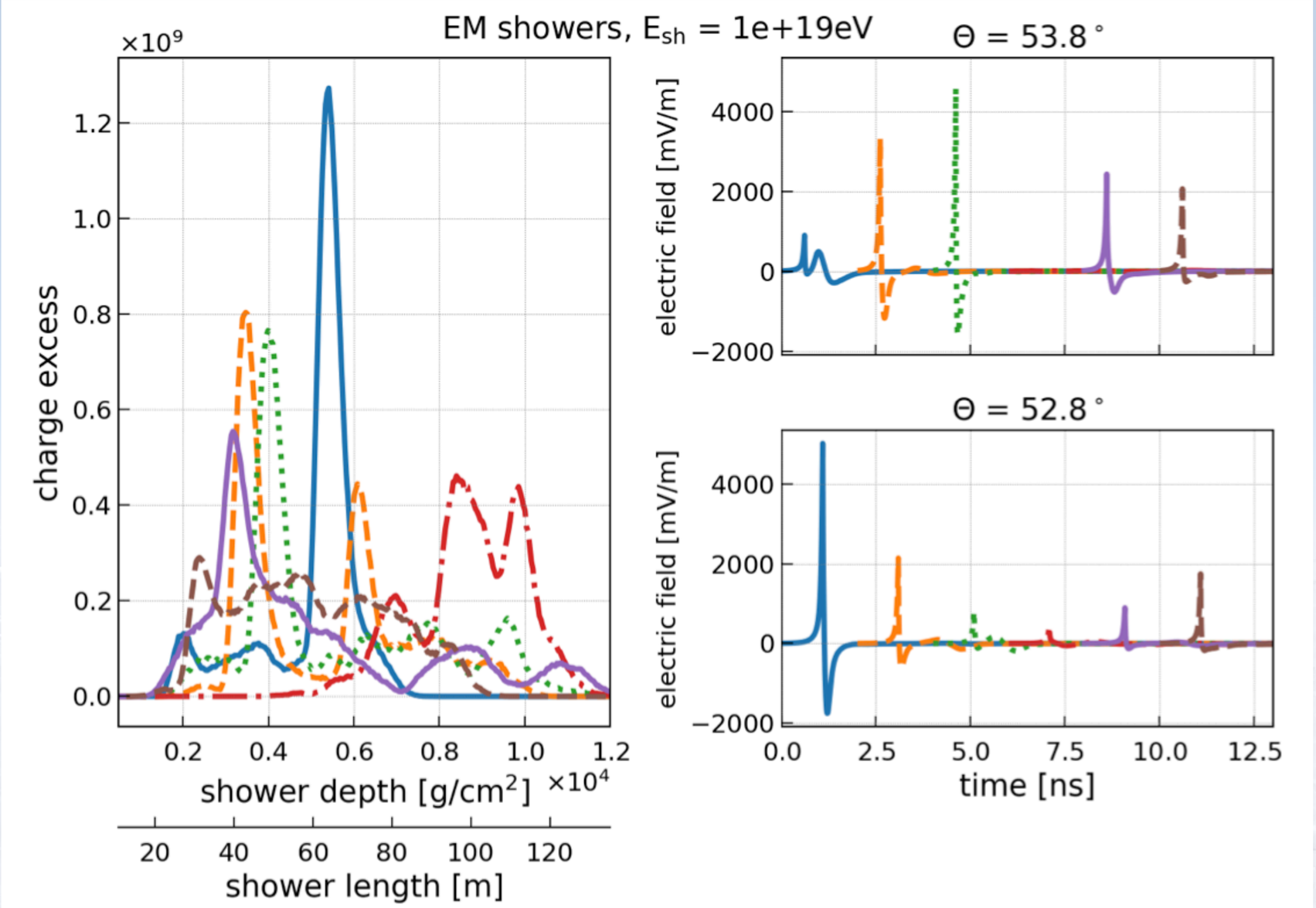
- Trigger runs on lower bandwidth (< 250 MHz), 8 beams are formed
- Design goal for threshold: amplitude_signal / sigma_noise = 2
- Technique demonstrated at South Pole by ARA [ARA, PRD 105]



Solar flare


Run 2123 event 3657
Power String
ch7
-43.3 m
ch6
-63.1 m
ch5
-83.1 m
ch4
-95.2 m
ch8
-96.1 m
ch3
-97.1 m
ch2
-98.2 m
ch1
-99.1 m
ch0
-100.2 m
Time, ns
Helper String C
ch21
-98.6 m
ch22
-99.6 m
ch23
-100.6 m
Time, ns
Helper String B
ch11
-84.9 m
ch10
-85.9 m
ch9
-86.9 m
Time, ns
Hpol
Vpol

LPM effect


EM showers, E_{sh} = 1e+19eV
×10⁹
charge excess
shower depth [g/cm²]
×10⁴
shower length [m]
Θ = 53.8°
Θ = 52.8°
electric field [mV/m]
time [ns]

Earth attenuation